DESIGN FOR MANUFACTURE THROUGH FABRICATION

A MANUFACTURING TIME AND COST ESTIMATION MODEL FOR LARGE FABRICATED ASSEMBLIES

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Thesis presented as partial fulfilment of Masters degree in Mechanical Engineering at the University of Stellenbosch

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Declaration

I the undersigned hereby declare that the work contained in this thesis is my own original work and has not previously, in its entirety or in part, been submitted at any university for a degree.

...24th... day of ...November... 19...98...

Abstract

This thesis concerns the development of manufacturing time and cost estimation models for large mechanical engineering assemblies. The objective of the time and cost models are to serve the design engineer as a tool for estimating manufacturing time and cost, as the design progresses from the conceptual to the detail design stage.

The manufacturing time and cost estimation models will give the designer the advantage of evaluating different concepts with time and cost as decision making criteria. The models can also be used as a redesign tool for existing products so that a cost comparison can be made between the existing and new design. The models can also be used as a design optimisation tool for the manufacturing time and cost of a new design or redesign. This will reduce unnecessary costs associated with a certain design

Basic process flow diagrams were determined from shop floor practice for each manufacturing process and its secondary process(es). Data for these models were obtained by time studies. The time study data was then used to investigate correlation's between manufacturing time and certain design parameters. Manufacturing time estimation formulae were then developed from the time study data.

Five major time and cost estimation models were developed and tested. The five models are: Welding Time Estimation for the Flux Core Arc Welding Process, Tack Welding Time Estimation, CNC Flame Profile Cutting Time Estimation, Manual and Mechanised Bevelling Time Estimation and Plate Bending Time Estimation. Each model depicts the manufacturing time and consumable requirements.

Opsomming

Die tesis handel oor die ontwikkeling van `n model vir die vervaardigingstyd en kosteskatting van swaar meganiese ingenieurstrukture. Die hoofdoel van die model is om `n gereedskapstuk te wees vir die ontwerpingenieur, waarmee hy die vervaardigingstyd en -koste kan skat vanaf die konsepontwerp tot en met die detailontwerp.

Die model sal die ontwerpingenieur daartoe instaat stel om twee konsepte teen mekaar op te weeg ten opsigte van vervaardigingstyd en -koste. Dit kan ook gebruik word as `n herontwerp gereedskapstuk vir bestaande produkte, sodat die nuwe ontwerp teen die oue opgeweeg kan word. Die model kan verder gebruik word as `n ontwerp-optimeringsgereedskapstuk vir beide `n nuwe en herontwerp. Dit sal lei tot die eliminering van onnodige vervaardigingskostes van `n spesifieke ontwerp.

Basiese prosesvloeidiagramme is opgestel vir elke vervaardigingsproses uit algemene werkwinkelpraktyk. Prosesvloeidiagramme is ook opgestel vir die sekondêre vervaardigingsprosesse. Tydstudiedata is opgeneem vir elke vervaardigingsproses en die gepaardgaande sekondêre proses(se). Korrelasies tussen beskikbare ontwerpparameters en vervaardigingstye is ondersoek met behulp van die tydstudiedata. Vervaardigingstyd skattingsformules is ontwikkel uit die tydstudiedata.

Vyf hooftyd en kosteskattingsmodelle is ontwikkel en getoets. Die modelle sluit in: sweistydskatting, geoutomatiseerde gasvlamsny, afskuinsing van plaatonderdele vir sweisvoorbereiding, plaatbuig en vashegtingsweis van onderdele. Elke model weerspieël die vervaardigingstyd en materiaalbenodigdhede.

Dedication

I dedicate this thesis to God and to my parents Anton and Ena De Swardt who has given me strength and motivation.

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Nomenclature

A	-	Average absolute error; Cross Sectional area of weld section
A_1	-	Mechanised bevel area
A_2	-	Manual bevel area
B	-	Number of curved bend sections on part
B_s	-	Back-set requirement parameter
C	-	True cost; Number of set-ups required for channel section; In plane curvature parameter
C_i	-	Individual estimated costs
C_{steel}	-	Specific heat of steel
C_{tot}	-	Total estimated cost
c	-	Y-intercept, central value
D	-	Distance of storage to bevelling area; Distance of assembly area from storage area; Depth to be back ground;
D_c	-	Depth of channel section
Disks	-	Number of grinding disks required
E_i	-	Error of estimated value against measured value
E_{tot}	-	Total error
H_{torch}	-	Heat output of torch
I	-	Welding current
ITF	-	Number of internal features on plate material
L	-	Length to be cut on plate material; Length of joining lines; Length of weld section; Length of weld section to be back gouged; Length of weld section to be back ground;
L_i	-	Length of bevel section; Length of curved bend section
M_i	-	Measured value
$M_{electrode}$	-	Total mass of electrode required
M_{Pack}	-	Mass of electrode per roll
m	-	Slope
m_1	-	Weight coefficient, first independent variable coefficient
m_2	-	Length coefficient, second independent variable coefficient
m_3	-	Joining line coefficient

m_4	-	Bent part coefficient
m_5	-	Material thickness coefficient
N	-	Number of parts on plate; Number of bevels on part; Number of same parts; Number of gouging passes required to obtain specified gouging depth
NL	-	Number of separate joining lines
NL_i	-	Number of lines to be marked
N_d	-	Number of data points; Number of double bevels on part;
N_s	-	Number of single bevels on part
n	-	Number of data points
P	-	Double bevel identification parameter; Power consumed
P_i	-	Estimated value
Pidle	-	Idle power consumption of welding machine
Q	-	Number of different types of normal bends in part
Q_i	-	Single to double bevel separator
Runs	-	Number of weld runs required to complete weld
r	-	Correlation coefficient
r_i	-	Residual value
S	-	Number of normal bends in part
Sx	-	X Sample variance
Sy	-	Y Sample variance
Sxy	-	Covariance
StartStop	-	Number of Start-Stop sequences for a specified weld length
T	-	Plate material thickness; Total welding time
Tarc	-	Arc time
T_c	-	Plate thickness separator
T_{basic}	-	Basic tack welding time
T_{grind}	-	Total back grinding time; Total surface grinding time
$T_{GrindingTime}$	-	Total grinding time on part
$T_{preheat}$	-	Preheating temperature
U_{dw}	-	Upper die width of bending press
V	-	Welding volts
Vol	-	Volume of steel to be preheated; Volume of weld metal required to fill weld section

W	-	Width of weld section on surface
W_c	-	Width of channel section
w	-	Mass of part
x_i	-	Measured x value
x_L	-	X-median of left group
x_M	-	X-median of middle group
x_R	-	X-median of right group
y	-	Estimated value of least squares fit
y_i	-	Measured y value
y_L	-	Y-median of left group
y_M	-	Y-median of middle group
y_R	-	Y-median of right group
z_i	-	Measured z value
η	-	Heat transfer efficiency, Power plant efficiency
ρ_{steel}	-	Density of steel

1. Introduction

1.1. Background

Research is being done in the field of Mechanical Engineering Design at the University of Stellenbosch. The research presented here was aimed at the development of fabrication time and cost estimation models for the fabrication of heavy engineering products. Other members of the research group focused on the development of cost and time estimation models for smaller assemblies that consited out of smaller and lighter parts.

The research was conducted at Barlows Equipment Manufacturing Co. in Boksburg, South Africa. Barlows Equipment Manufacturing specialises in the manufacturing of earth moving equipment and agricultural equipment for timber industry.

1.2. Literature Overview

Manufacturing became more competitive around the world during the 1980's and it has been shown that the key ingredients in a manufacturing company's viability are product innovation, quick development and bringing quality products to the market [Hundal, 1995].

In the beginning of the 1980's, there was a general move to introduce automated manufacturing in the USA. This was mainly driven by two interests. Robots had recently become available and engineers wanted to obtain hands on experience, to understand how automated manufacturing could be utilised to improve productivity [Helander, 1994]. The sudden increase in the value of the U.S. dollar, also made it more difficult to compete with countries that had cheap labour. Automation was perceived as a major weapon to enhance the competitiveness of the U.S. industry.

The results of automation were, however, somewhat disappointing. During the 1980's General Motors invested $80 billion in automated manufacturing, but at least 20% of their spending failed [Helander, 1994]. Therefore, by looking at the manufacturing cost from the design stage (with the use of cost models and design rules) instead of just at the manufacturing stage, one will be able to reduce manufacturing cost with manual and automated manufacturing processes.

South Africa's economic situation drastically changed when the political situation changed in 1994, which resulted in the start of South Africa's readmission to the international market place. The government was forced to drastically cut back on their defence budget and re-allocate their resources to other government funded projects. Many industries subsequently suffered as a result of this sudden loss of income, followed by the sudden exposure to the international market place. South African industries have since had to adapt to these new conditions they faced.

The international marketplace is characterised by fierce competition, but also many opportunities. To take advantage of the opportunities, the local industry must achieve the same standards as the international manufacturers at a competitive cost to survive. This highly competitive marketplace requires manufacturers to deliver products of high quality to their customers on time and at low cost [Hundal, 1993; Hundal, 1995].

The requirements of the competition in the international market place, has also shifted the emphasis of product development to be more time and cost driven, as opposed to the conventional primary focus on design for performance [Hundal, 1995]. Performance will always stay the primary focus of the designer but if he can maintain the same standards of performance at a lower cost then he will have produced a better design.

It was recognised that design is a core element in the development and manufacturing of competitive products. Studies indicated that 70-80% of the factory and life cycle costs are set at the design stage whereas the design stage itself only accounts for about 6% of the products cost [Hundal,1993; Boothroyd et al. 1994] . Because of this the design department ought to have the most information about costs, but unfortunately this is not the case in most companies [Hundal, 1995]. Figure 1.1 depicts the product costs set and incurred in different activities. The 70% product cost fixed in the design office can be attributed to the customer requirements and the design itself. The specifications should be dictated by the customer's needs, expectations and problems, benefits to the customer and expected improvement over existing products. The specifications should, also, pay particular attention to the environment in which the product will operate [Hundal, 1995]. Therefore, designers ought to have cost information about existing products that have similar specifications.

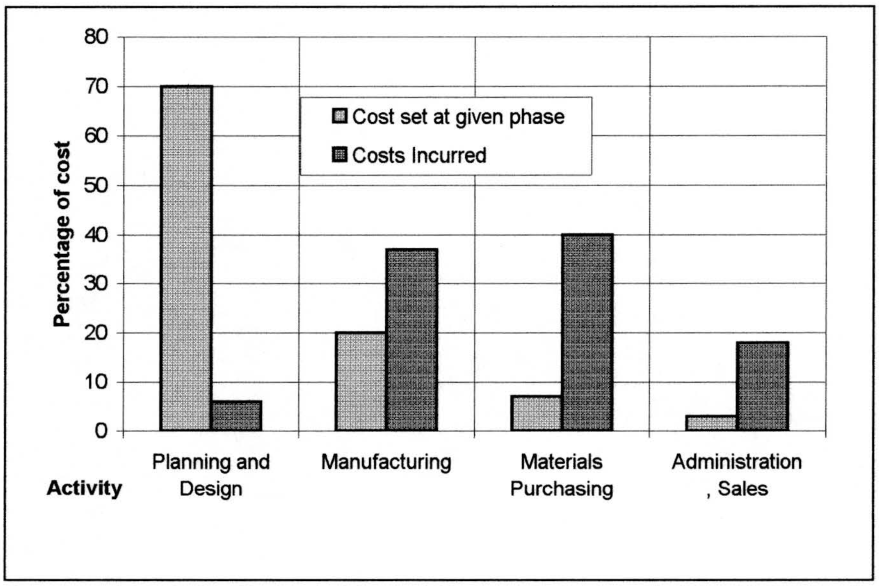

Figure 1.1 Product cost set and incurred with different activities [Hundal, 1995]

According to Blanchard and Fabrycky, 1990, the development of a product can be seen as a consumer-to-consumer process, with the following stages:

- The identification of a need by the consumer
- Planning
- Research
- Design
- Production and evaluation

- Consumer use
- Maintenance and support
- Retirement

A combination of manufacturers, designers and consumers are involved at every stage. It is essential that engineers be sensitive to operational outcomes during the early stages of system development, and that they assume the responsibility for life cycle engineering which has been largely neglected in the past [Blanchard and Fabrycky, 1990].

The life cycle engineering design approach for bringing competitive products to the market considers the total life cycle of the product, the life cycle of the manufacturing process and the life cycle of the product service system. The objective is to consider the entire life of the system from inception. The design process must therefore obtain inputs from all parties involved in the product's life cycle. This includes the customer, production planning, manufacturing, marketing, salvage handlers and logistic support [Blanchard, Fabrycky, 1990; Hundal, 1995]. To ensure economic competitiveness with regards to the end product, engineers must become more closely associated with economics and this is best accomplished with the life cycle approach [Blanchard, Fabrycky, 1990].

It is also known that the total product cost are influenced by all stages of its life cycle -from design to product phase out. The most important factors that influences the product cost are [Hundal, 1993]:

1. The concept, including physical effects, material type, number and type of active surfaces.
2. The size of the product.
3. The number of parts that make up the final product, including the standard required and similarity between parts.

Product manufacturing costs can be lowered with the implementation of automated manufacturing. This approach is, however, limited to particular circumstances [Helander, 1994]. Automation can yield results on the long term by speeding up the product manufacturing phase in dedicated production lines. Automation is expensive because the cost of equipment acquisition and set-up costs are extremely high. Furthermore, the greater the diversity of products manufactured on the production line, the more expensive the equipment [Helander, 1994].

Designing for ease of manual assembly with the aid of design rules and cost models will give an indication of ease of assembly and manufacturing cost. This will help in determining the feasibility of automated equipment.

People seem to profit, in most cases, from the identical principles that simplify automated assembly [Helander,1994]. Therefore, designers should look at human factors when designing for automated assembly. These include:

1. Provide foundation and fixture.
2. Minimise the number of parts.
3. Facilitate handling of parts.
4. Facilitate orientation of parts.
5. Consider stability and durability.

In other words, make the job for the man that has to build it as easy as possible .

Traditionally designers worked with the attitude of "We design it and the workshop builds it" [Boothroyd et al. 1994]. This resulted in the designer designing a product without giving much thought to the manufacturing of it and hence the costs associated with manufacturing.

1.3. **Design for Manufacture and Assembly (DFMA) Overview**

Design For Manufacture and Assembly techniques originated at the beginning of the 1980's. It comprises the use of design rules and cost models to lower the costs and time of production. DFMA works concurrently with the design phase of new products. It can also be implemented as a re-design tool to reduce manufacturing costs of existing designs while still maintaining the functionality, performance and manufacturing quality of the end product.

DFMA embraces human factors, design rules and cost models that influence a design outcome with regards to manufacturing. Cost models relate certain design parameters to the final product cost so that design alterations can be made when it is most feasible to make changes to the design.

The term "design for manufacture" means the design for ease of manufacture of different parts that will make up the final assembly and "design for assembly" refers to the design of parts for ease of assembly [Boothroyd,1994].

Frequently, it is at the stage of manufacture that problems with the design are encountered. The production shop then has to make requests for design changes. This will be followed by a design review. Making changes to the existing design will delay the product release date and hence increase the final product cost [Boothroyd et al. 1994]. These problems are random and they can occur at any stage in the manufacturing phase. It is known from experience that the later the problem is detected in the production phase, the greater the delay and the higher the cost of rectifying the problem [Boothroyd et al. 1994].

DFMA looks at the implications that the design has on manufacture from an early stage in the design cycle, and therefore gives designers the ability to make manufacturing related design changes before the product goes into its production phase [Boothroyd et al. 1994; Hundal,1993; Hundal, 1995]. This will minimise the cost of expensive design alterations.

Provision of cost information must at least include the following departments; process planning, purchasing, cost engineering and design engineering [Hundal, 1995]. The purchasing department can provide the designers with specialised knowledge and information about typical purchased items, supplier cost structures and help in building a user friendly cost database. The process planning department can provide the designers with the necessary cost information related to the different manufacturing processes used, develop a strategy for deciding between make or buy and provide information about in-house and external production facilities. The cost engineering department provides cost comparisons of similar parts, assemblies and products so that early design changes can be made at the layout design stage. DFMA should also give relative cost information between manufacturing processes, materials, part groups etc.

It is therefore the authors opinion that, by giving designers the ability to estimate manufacturing time and cost of a design. Designers will, therefore, be able to assist other departments with their functions by giving them a clear set of requirements applicable to them.

The time and effort spent on the DFMA analysis, at the design stage, will be recouped by preventing the losses which could be encountered during the production phase [Boothroyd et al. 1994]. DFMA will also help designers to design for a specific process and optimise the design for that process, if this process is the only one available.

To take more advantage of concurrent engineering, the design team will need DFMA cost models to determine the outcome of a design's manufacturing costs. This will give the designers the opportunity to do trade-off studies between different concepts in a design with product cost and product development time as additional decision making criteria.

The basic steps taken to implement DFMA, on an integrated basis, is shown in Figure 1.2.By implementing the DFMA analysis tools within this framework, manufacturing companies can only yield desirable results. It will reduce costs due to the following [Hundal, 1995]:

1. The development time will be shortened thus reducing development cost.
2. Reduced probability of mistakes because designers receive rapid feedback.

3. Fewer design iterations will be required.
4. The analysis for the redesigning of a product will yield problem areas and references with which the new design can be compared.

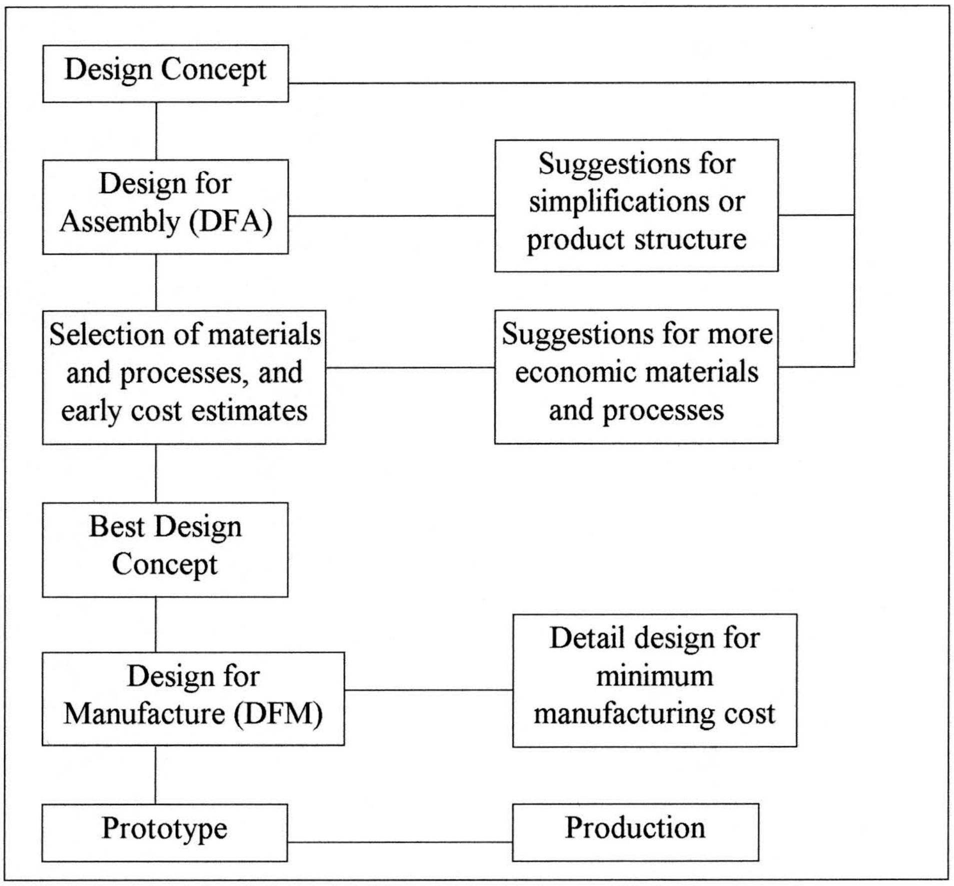

Figure 1.2 Design steps taken in simultaneous engineering using DFMA techniques [Boothroyd et al. 1994].

The advantages of applying DFMA are [Boothroyd et al. 1994]:

1. It provides a systematic procedure for analysing a design from the point of view of manufacturing and assembling. It results in simpler and more reliable products. DFMA also reduces part-count which has a snowball effect on overall product cost.
2. It improves communication between all parties involved who have an influence on the manufacturing cost.
3. The saving in manufacturing costs as a result of DFMA techniques is astounding [Boothroyd et al. 1994].
   - Texas Instruments improved the assembly time by 84.7%, reduced

the number of different parts by 66.7%, reduced the total part-count by 74.5%, reduced the number of operations required by 77.6%, reduced metal fabrication time by 71.1% and reduced the product weight by 45.8%

- NCR reduced the number of suppliers by 65%, the assembly time by 75%, the assembly tools required by 100% (plastic snap fittings), the part-count by 85% and the overall manufacturing cost by 44%.
- Motorola improved their assembly efficiency 800%, assembly time by 87%, assembly count by 78% and reduced the number of fasteners by 100% (snap fittings instead of screws).

1.4. **Design Rules**

Design rules help designers early in the design cycle, to focus their attention on the manufacturing of their design concepts.

Design rules are based on experience and generally not quantified or expressible in algorithmic form. They relate certain parameters to properties of interest. Design rules help in decision making [Blanchard and Fabrycky, 1990], but they can create a mind-set and preclude innovative solutions, which is just the opposite of what one strives for in design [Hundal, 1993]. Design rules can also contradict each other, in which case further analysis is required. It is the authors opinion that design rules should be used in conjunction with costing algorithms. The following basic design rules can be used to reduce the total product cost [Hundal, 1993]:

1. At the problem definition stage, ask for fewer demands: Only the minimum accuracy and tolerances and conformance to standards.
2. At the concept stage, use concepts which lead to smaller sizes and lighter construction.
3. Use higher speed for power transmission, thus reducing the torque and consequently the amount of material required.
4. Use parallel paths for flow of energy.

5. Use robust physical effects, e.g. mechanical and hydrostatic energy.
6. Use concepts with simple construction and fewer parts by use of function integration, especially for small products and/or large quantities.
7. Use smaller parts for one-of-a-kind products. For large quantities smaller size always leads to lower costs.
8. Use same and/or similar parts.
9. Produce in large quantities. This results not only in an economy of scale, but also that more optimum manufacturing processes can be used.
10. Reduce complexity: Use fewer parts and production operations.
11. Reduce size, thereby the material volume.
12. Use safety devices so that the device will not have to be designed for high loading which only occurs occasionally.
13. Use higher strength materials and/or surface treatment to reduce the product size and generally the manufacturing cost.
14. Use fewer machining operations by using integral designs, this also reduces the set-up costs.

1.5. **Cost Models**

The development of cost models for a product requires the identification of a product cost structure. A cost structure shows the breakdown of the product cost according to one of several criteria: parts, functions, production processes etc. Cost structures can be classified into one of the following types [Hundal, 1993]:

- Organisational, based on departments and units
- Generational, based on elements and features
- Functional, based on functions of the product
- Work, or activity-based costing.

The cost models developed within this thesis are work based and are build around the actions of the worker.

Designing for a cost goal or minimising costs will best be possible if it is carried out concurrently as the design progresses from the concept to detail design phase. It requires quick costing with a simple method based on the cost entities which are available at a specific stage of design. All cost structures require a cost model to do the costing tasks.

Cost models for estimating manufacturing costs at the design stage can be categorised into the following [Hundal, 1993]:

- Based on operations - These models can only be used in the final design stage.
- Based on activities - The model makes use of all activities associated with the product.
- Based on weight and material - Allows cost estimation for products for which material costs dominate.
- Use of physical relationships - Most commonly used and obvious method of minimising costs during embodiment. For example a stress equation can relate to load and material required.
- Application of regressional analysis - The dependence of costs on product characteristics such as size, weight, etc.
- Application of similarity principles - These models are only used when the design is scaled.

More detail of available cost models, if any, for the manufacturing processes described in this theses are presented in subsequent chapters.

1.6. <u>The Fabrication Processes Involved</u>

A study of production processes for large fabricated mechanical engineering products identified the following manufacturing processes which are commonly used in the fabrication of products from plate material [Amstead et al. 1987; Boothroyed et al. 1994; Carry, 1992; Farkas, Jarmai, 1995]

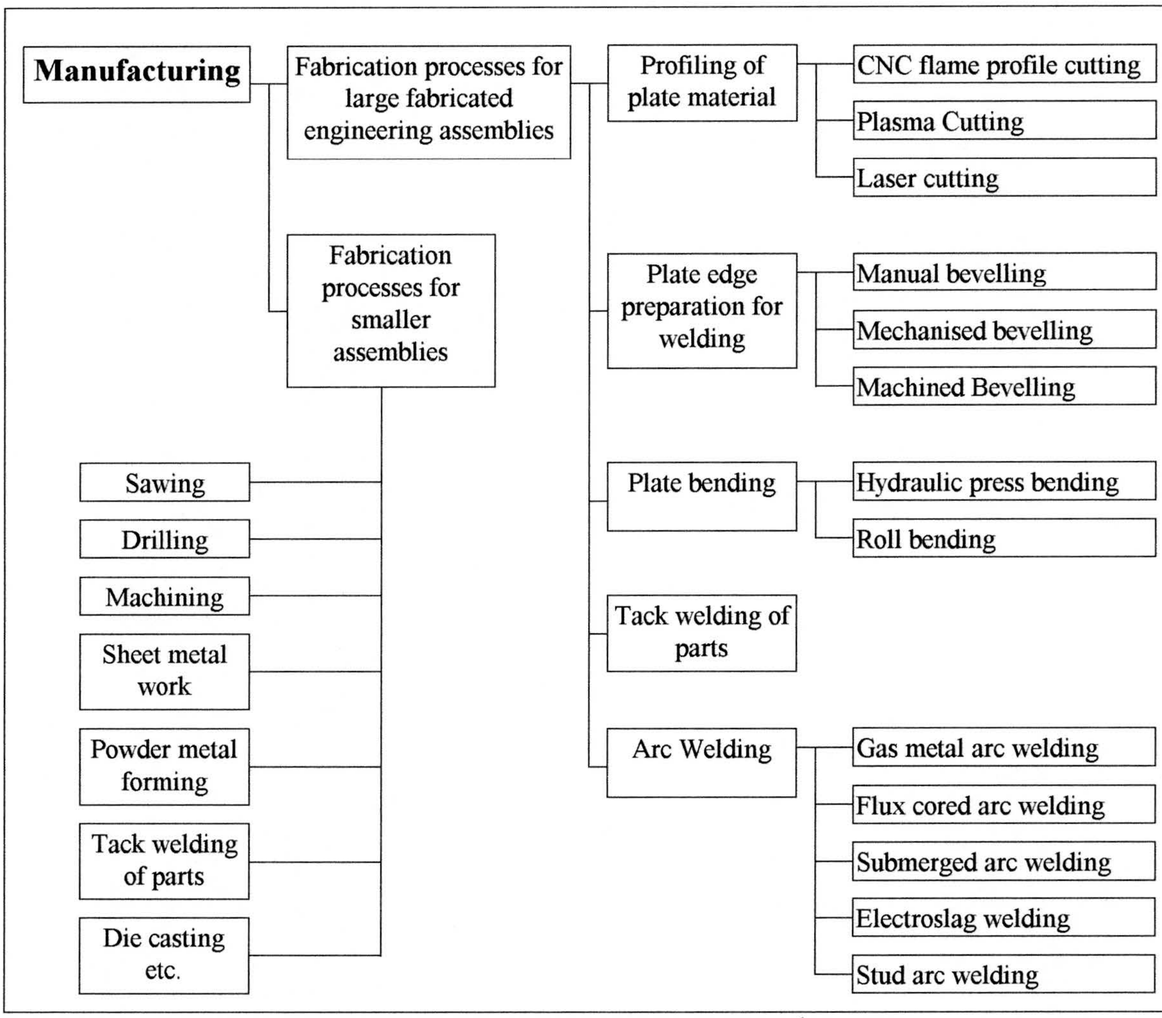

Figure 1.3 Manufacturing processes[1]

Other members of the research group focused on the development of cost models for manufacturing processes that were more appropriate for smaller assemblies. Much has also been done in the field of cost estimation for these manufacturing processes. Boothroyed et al. 1994, portrays most of the cost estimation models associated with processes for smaller assemblies in detail.

The fabrication processes that were identified for further investigation in this theses were:

- CNC profile flame cutting of plate material.
- Manual and mechanised bevelling for welding joint preparation.
- Plate bending with a hydraulic press.

[1] The reader can refer to the mentioned references should he require detail information about the mentioned processes

- Assembly and tack welding of a set of parts.
- Welding of sub-assemblies and overall assembly using the flux core arc welding process.

These processes were chosen, mainly, because of their availability in the research plant.

Most of these manufacturing processes require secondary processes which are influenced by standards of manufacturing, safety, aesthetic considerations of the product and the judgement of the designer. The chosen manufacturing processes and their secondary processes are summarised in Figure 1.5.

Process flow diagrams were developed for all the processes described in Figure 1.5. These process flow diagrams reflect the tasks and the task sequences that are required to process a part or set of parts with given attributes. An example of a process flow diagram for making instant coffee is shown in
Figure 1.4.

The considerations involved in deciding whether secondary processes are employed, are outlined in the following paragraphs.

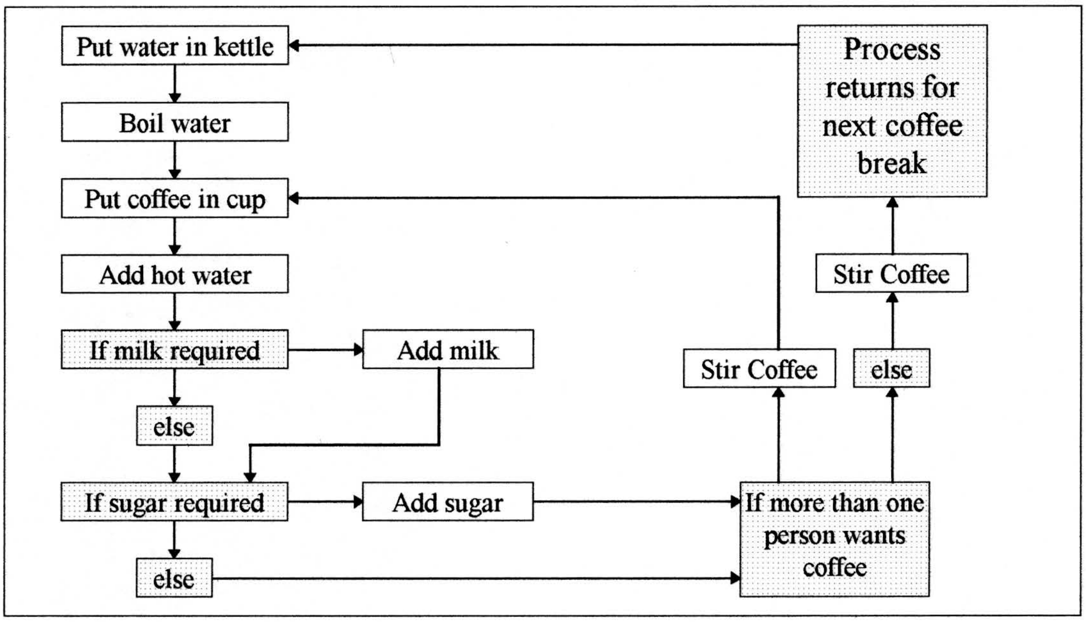

Figure 1.4 Process flow diagram for making instant coffee

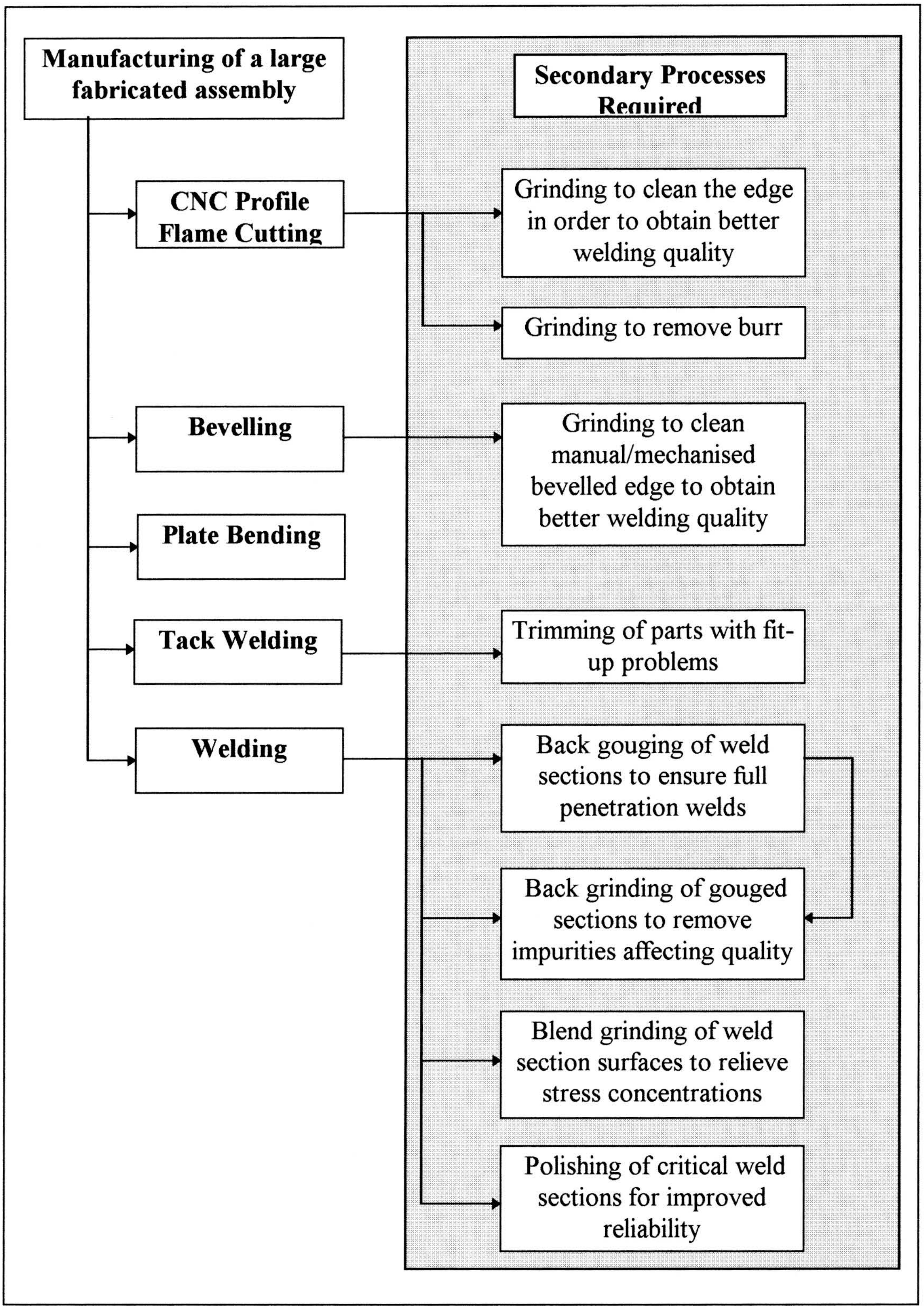

Figure 1.5 The manufacturing processes and their secondary processes for large fabricated assemblies

1.7. **Secondary Processes Description**

1.7.1. ***CNC Profile Flame Cutting Secondary Processes***

The secondary process for CNC flame profile cutting is burr removal grinding, where the burr produced by the cutting flame is removed with an air grinder.

The employment of secondary processes for CNC profile flame cutting is influenced by :

- Safety of part handling by operators during the subsequent manufacturing operations of the final product.
- Aesthetic reasons, e.g. the removal of scale from the surface of the cut edge to improve the quality of painting
- Improvement of the quality of weld sections by removing scale from the material surface.

1.7.2. ***Manual and Mechanised Bevelling Secondary Processes***

The secondary process for manual and mechanised bevelled edges is clean grinding of the bevelled surface with an electric grinder.

The employment of secondary processes for bevelled edges is influenced by:

- The quality of welding, which may require the removal of scale (low volume of metal removed).
- To ensure a smooth welding surface, especially for manually bevelled edges (high volume of metal removed).

1.7.3. ***Tack Welding Secondary Processes***

The secondary process for tack welding includes trimming with a hand held torch and the subsequent clean grinding of the newly cut surfaces.

The employment of secondary processes for the tack welding process is influenced by:

- The tolerances of the components. Trimming of parts is necessary when the fit-up of a part is poor. The amount of trimming required is directly linked to the quality of the preceding manufacturing operations, i.e. CNC profiling accuracy, bevelling accuracy and bending accuracy.

The study also showed that trimming of parts are related to the part complexity. Bent parts required trimming more often than flat parts.

1.7.4. ***Welding Secondary Processes***

The secondary processes of welding are primarily determined by decisions made by the designer at the design stage. These include:

- The placement of a weld section in a highly stressed region
- Weld joint design

A weld section that requires full penetration is often back gouged and back ground to ensure the removal of all impurities, such as oxides and flux inclusions, which are inherent to the welding of a root run. Surface grinding, and often polishing with a sanding disk, of the welded surface are required to remove undercut, hence removing stress concentrations. These operations are mainly aimed at improving the weld section's performance.

1.8. **Manufacturing Process Reduction**

The manufacturing processes and the secondary processes required to form a product were broken down into smaller time elements in order to identify recurring tasks. A time element is defined as the time that it takes to perform a simple task (e.g. put coffee in cup,

Figure 1.4) The time elements that were derived from the time study data can be divided into two categories:

1. Constant time elements which are generally associated with minor tasks within a manufacturing operation (e.g. Stir coffee,
2. Figure 1.4.)
3. Variable time elements which are fixed by the part or product attributes (e.g. Add sugar,
4. Figure 1.4., which are related to the sweetness of the coffee).

The constant and variable time elements are combined in the same sequence as in the manufacturing process flow diagrams and secondary process flow diagrams when the manufacturing time is estimated.

1.9. **Thesis Objectives**

The main objective of the research was to develop a manufacturing cost estimation model for the design for fabrication of large and heavy engineering products. The model has to estimate the direct manufacturing cost of a fabricated product with the inputs that are available during the embodiment design stage and which are known to the designer.

Research was done on large mechanical engineering assemblies, such as earth moving equipment, which are built up from steel plate material.

1.10. **Research Relevancy**

The literature study done couldn't find a concise manufacturing cost estimation model for large fabricated engineering assemblies. Available costing methods mainly focuses on the costing of welding and considers the lower level manufacturing processing costs (e.g. weld joint preparation) to be proportional to the welding cost. It was therefore required to develop a series of cost estimation models, that will estimate the costs associated with each manufacturing process and its secondary processes.

The aim of the Manufacturing cost estimation models are:

1. Identify the cost drivers of the design and to identify areas of high cost for each manufacturing process.
2. Give relative cost information between two or more design alternatives.
3. To be used as a redesign tool for existing products for lowering existing manufacturing costs.

1.11. **Research Approach**

The approach taken for the research program was:

1. Identify the relevant manufacturing processes for the manufacture of large fabricated assemblies. Develop a detailed process flow diagram for each of the manufacturing processes. These diagrams depict the tasks (or time elements), that the operator has to perform for a manufacturing process.
2. Identify the secondary processes required for each of the manufacturing processes and determining the relationship between the primary and secondary processes.
3. Record time study data for all the identified manufacturing processes and their secondary processes.
4. Investigate correlation's between the inputs from the designer, and the time and cost of manufacturing the product.
5. Asses the accuracy of the models.

2. Data Collection

2.1. Recording Methods Used

Data for all the manufacturing processes were recorded by motion and time studies. This data can be used to determine the standard number of minutes that a qualified, properly trained and experienced person should take to perform a specific task or operation when working at a normal pace [Barnes, 1980; Niebel, 1988]. This time standard may be used for planning and scheduling work, for cost estimating, or for labour cost control, or it may serve as the basis for a wage incentive plan [Barnes, 1980]. The operation to be studied is divided into small elements, each of which is timed with a stop watch. A selected or representative time value is found for each of these elements, and the times are added together to obtain the total selected time for performing the operation [Barnes, 1980].

The time studies were recorded with a video camera or a stopwatch. The motions of the operator were also monitored. This was done to obtain the process flow diagrams presented in this thesis. The measured time was then divided according to the time elements depicted in the process flow diagram of each manufacturing process and its secondary process(es).

Data recorded with the video camera was more accurate than the stop watch method. Video data also had the advantage of being able to be reviewed so that outlying data points could be investigated, something which may not be evident when recording data with a stopwatch. Time data with a stop watch had the advantage of obtaining data which could not be measured easily with a camera, such as the normal reach of an operator (something which can be annotated conveniently next to the time interval) for manual bevelling and welding. This is because the normal reach cannot be obtained from the assembly or part drawing. Both methods of data recording had an improving effect on the operators efficiency with regards to non-productive times.

Operators were informed before any data were recorded. The objectives of the study were discussed with them and it were made clear to them that the recorded time is not to check them up. In general the confidence of the operator had to be obtained before recording any data. Operators were also asked to convey problems such as fit-up problems, blocked cutting nozzle, broken wire feeder etc. to the analyst, to identify aspects not related to the design, but that influence the measured times.

Non-productive times were not included in the reduced time study data. The time elements presented in this thesis are therefore based on a 100% productivity. The total time needed to complete a process can be calibrated to give a more accurate absolute time and cost prediction, by multiplying the 100% productive estimated time with an operator efficiency factor.

2.2. <u>**Statistical Analysis**</u>

Basic statistical analysis were used because the purpose of the models is to give a designer an indication of direct manufacturing costs associated with the design parameters, not for quoting purposes. It is there to give relative answers about fabrication time and cost especially when design alterations are made.

Constant time elements were determined by taking the median of the recorded times (e.g. set-up time). Median values have the advantage of not being as sensitive to extreme data points as average values.

Variable time elements were determined with:

- The median speeds recorded
- With function fitting through median values with the least squares method
- Robust data analysis (resistant lines for y versus x) [Hoaglan, 1982]

The median speed method have the advantage of not being as sensitive to extreme data points as the other methods mentioned. The main disadvantage of the median speed method is that it needs a fairly evenly distribution of data (y vs. x) in order to be used with accuracy over the specified range of data points.

The least square method is very good to use when a large number of data points are available (especially for a first approximation). This method can also be used easily when the problem involves more than one independent variable (multiple linear regression). The main disadvantage of this method is that it is extremely sensitive to extreme data points which can cause erroneous predictions. This can be attributed to the method's attempt of weighing the errors on quadratic basis.

The resistant line technique fits a straight line through a set of data points. It first divides the data into three groups and achieves resistance by using medians within the groups. An initial line is then fitted to the three median points. Residues are then calculated and another resistant line is fitted to the residues. A new set of residues are then calculated and the slope and intercept is summed to the initial slope and intercept. The iterative process stops when the slope and intercept of the line fitted through the latest set of residues is smaller than 0.1% that of the initial slope and intercept. This method therefore attempts to produce an even scatter of errors around the fitted line. The main requirement (or disadvantage) of the resistant line technique is that the data set must be formed into three groups of as nearly equal in size as possible.

All constant and variable time elements, determined as shown above, were used to calculate estimated times and were compared to the recorded times. The constants and functions were then evaluated in terms of the errors produced, standard deviation and the confidence with which they can be used. The method that produced the smallest errors with a specified confidence (90%), over the recorded range, where then chosen as the best estimation method.

A Monte Carlo (Series of Events (Point Processes)) analysis was also performed for all the models presented within this theses [O'Connor,1991]. The analysis was done to show the effect of partial error cancellation of the underlying time elements. The analysis is however restricted to the scenario being analysed, because certain time elements (variable elements, e.g. bevelling cutting time) are dependent on part attributes. The occurrence of all time elements also afects the outcome of the Monte Carlo analysis. The occurrence of time elements is something which is also fixed by the part attributes and batch size. The analysis were, therefore, done for the verification scenarios presented in Model Verification on page 155.

A more comprehending review of the statistical methods employed are given in Appendix H.

2.3. **Definition of Error Terms**

The comparison of predicted and the recorded data required the definition of an error term. The recorded time elements were used as basis for the error calculations. The error term therefore gives an indication of how far the estimated time is from the recorded time, as a fraction of the recorded time:

$$E_i = \frac{P_i - M_i}{M_i}$$

The average absolute error is defined as follows:

$$A = \frac{\sum_{i=1}^{N_d} \operatorname{abs}(E_i)}{N_d}$$

The overall error is the error that compares the sum of the estimated time elements with all the recorded times of the corresponding elements. This error is defined as follows:

$$C = \frac{\sum_{i=1}^{N_d} P_i - \sum_{i=1}^{N_d} M_i}{\sum_{i=1}^{N_d} M_i}$$

According to Hundel [1993] the total estimated cost of a unit is a summation of separate items: cost of standard parts, manufacturing costs, material costs etc. If the individual estimated costs C_i have errors E_i which are uniformly distributed around he true cost C, then the total estimated cost

$$C_{tot} = \sum_{i=1}^{n} C_i$$

will exhibit a smaller total error E_{tot} than do the individual costs C_i. This comes about due to the partial cancellation of positive and negative errors.

2.4. **Formula Construction and Implementation**

Time elements of each manufacturing process and secondary process were combined, with the aid of the detailed process flow diagram, to obtain manufacturing time estimation formulas for each process. The formulas mainly focus on production time estimation requirements. Where applicable, the model also estimates the consumable required. The production time can be used with the labour rates to obtain the labour cost. The material requirements can be obtained from the bill of materials. The material cost can be determined from suppliers cost charts. Material, consumable and labour costs can then be combined to get the total direct product cost and to identify the main cost drivers of a design. In this thesis a cost driver is defined as anything that drives the total direct cost up, for instance, high labour costs compared to material cost can be attributed to high welding cost, which in turn can be attributed to large weld sections.

Different design alternatives can then be compared with cost and time as a decision making parameter. The main cost drivers can be analysed further to reduce the manufacturing costs (e.g. reduce labour costs by reducing the weld metal deposit). The labour time required for a design can help in production planning at an early design stage.

3. CNC Profiling Time Estimation

3.1. Overview of CNC Flame Profile Cutting Process

CNC flame profile cutting is an oxygen-cutting process used to cut parts from plate material. The cutting torch is used to heat the steel to the metal's kindling temperature. Introducing a stream of oxygen to the preheated steel, causes the burning or rapid oxidation of the steel. The stream of oxygen assists in removing the molten steel from the cut.

Steel and a number of other metals can be flame cut with this process. The following conditions must be met [Cary , 1992]:

1. The melting point of the material must be above its kindling temperature.
2. The oxides of the metal should melt at a lower temperature than the metal itself.
3. The heat release created by the combustion of the metal and oxygen must be sufficient to sustain the oxygen cutting operation.
4. The thermal conductivity of the metal must be low enough so that the material can be brought to its kindling temperature at the point being cut.
5. The oxides formed during the cutting process should be in a fluid state so as not to interrupt the cutting operation.

The cutting process can use any type of gas fuel. Each fuel has its own characteristics and settings, but the general concept of the cutting process stays the same. The most common fuels are LP-gas and acetylene [Cary,1992 , Logan,1991, Afrox,1996]. The main difference between LP-gas and acetylene in the cutting process, is the cutting speed that can be obtained:

- LP-gas cutting tends to be slower than acetylene, especially in thinner plates, because acetylene has a greater heat release per mole than LP-gas. Therefore, the material's kindling temperature will be reached faster. Acetylene, also uses less oxygen for the preheating flame. The greater heat release of acetylene also facilitates a faster piercing operation.

- LP-gas cutting is, however, more cost effective when cutting thicker plates (150mm and above) because the effect of the heat release of the preheating flame, becomes less compared to the heat release that is obtained by the oxygen iron reaction. The main disadvantage of acetylene is its cost compared to LP-gas.

In order to make the cutting process as economical as possible, the manufacturer must optimise their CNC flame profile cutting production line, by keeping the duty cycle of the machine as long as possible. Manufacturers must consider in house cutting vs. sub-contracting of material cutting.

A rotating bevel head can also be used in the cutting process to reduce subsequent bevelling operations on parts, and hence the overall production time. This should only be considered if the average part produced in the plant has many bevelled edges [Logan,1991].

When cutting plate material with the CNC flame profile cutting machine, the preheat flame heats the surface of the material up to its kindling temperature. The operator then starts the cutting oxygen flow, upon which cutting commences. In thicker plates, the upper surface of the plate reaches its kindling temperature much quicker than the lower surface, resulting in a large temperature gradient across the plate thickness. This causes some of the molten metal to jump back onto the nozzle, partially clogging it. Some of the metal also solidifies around the pierced hole, causing obstruction to the cutting nozzle movement. The cleaning of pierced holes is only necessary if the plate thickness exceeds 30 mm. Thicker plates also require the cutting of a square or circle around a pierced hole in order to obtain a uniform cutting edge.
After the part has been cut, it is removed from the CNC machine bed and it is ready for grinding (grinding of the plates edge).

3.2. Time Estimation Model for CNC Flame Profile Cutting

3.2.1. *Model Construction*

The total CNC flame profile cutting time, of a whole plate, is broken down into smaller time elements. These time elements are related to specific operator tasks and machine cycle times. Each element is calculated separately and combined in a predetermined manner with the other time elements (as depicted in the process flow diagram , Appendix A) to obtain the total CNC flame profile cutting time.

The time study showed that the CNC flame profile cutting time can be broken down into the following time elements:

1. CNC machine set-up time (moving of the CNC machine to the previously positioned plate material, setting up the cutting nozzles, loading of data into the computer, igniting the flames and positioning of the nozzle for the first piercing operation).
2. De-set-up times of the CNC profiling machine (all operations needed to stop the process so that the already cut parts can be removed).
3. Cutting time.
4. Re-set-up times or piercing times (time needed to move the nozzles and pierce the plate when there are two or more cut sections on the plate material).
5. Material set-up time (time needed to load and position the material on the machine bed).
6. Part removal time.
7. Crane connecting times for part removal.
8. Scrap removal times
9. Pierced hole cleaning time.
10. Operator movement needed for part removal (retrieving the crane after a part has been removed from the profiling bed).

The CNC flame profile cutting process also requires grinding and handling (secondary processes), that has to be performed on a part or the material before it can be processed further or signed off.

This model focuses on the use of LP-gas as the fuel of the cutting process. Recorded cutting speeds from the workshop were also compared to the cutting speeds recommended by Afrox [1996]. Recorded speeds of the workshop were, for thinner plates, less than the speed recommended by Afrox. Recorded speeds of thicker plates were faster than the cutting speeds recommended by Afrox.

This model does not directly take the effect of part nesting into account. Designers can calculate a yield factor (utilised plate area/purchased plate area) that will indicate the plate utilisation efficiency. Designers will, therefore, see the benefit of nesting a part with other parts or with multiples of itself, if he tries to maximise the yield factor.

The input requirements for this CNC flame profile cutting model includes:

1. The number of plates required to produce the parts of an assembly.
2. The plate thickness of each plate.
3. The length and width of each plate.
4. The number of parts nested on each plate.
5. The number of internal features (such as holes in a part) on each plate.
6. The total length to be cut on each plate.
7. The total utilised area of each purchased plate.

It is the impression of the author that designers can keep production cost of CNC flame profile cutting as low as possible by taking note of the following:

1. Keep the cutting distance on a part as short as possible.
2. Design parts so that they can be nested on the as purchased plate in order to maximise plate utilisation.
3. Avoid the cutting of unnecessary internal holes in parts if possible, especially when the plate thickness is more than 30mm. Internal features

should only be added if absolutely necessary (e.g. flame cutting of holes instead of machining).

3.2.2. ***Constants for CNC Flame Profile Cutting***

The time study data was used to determine time constants for the above mentioned time elements (Appendix A). Correlation's between cutting speed vs. material thickness and piercing time vs. material thickness were determined.

The terms and constants used by the time estimation model are as follows:

CNC Machine Set-up Time = 600 seconds

Definition:

Total time to load CNC program, position machine, position cutting nozzle(s) according to job card, igniting flames, correcting gas-oxygen mixing ratio, positioning the machine and switching machine to automatic control.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	37%
Cumulative error	-2%
Standard deviation the error	57%
Lower confidence limit of 90%	-29%
Upper confidence limit of 90%	29%
Reference	Appendix A.1.1 page A-II

Table 3.1 Properties of CNC machine set-up time

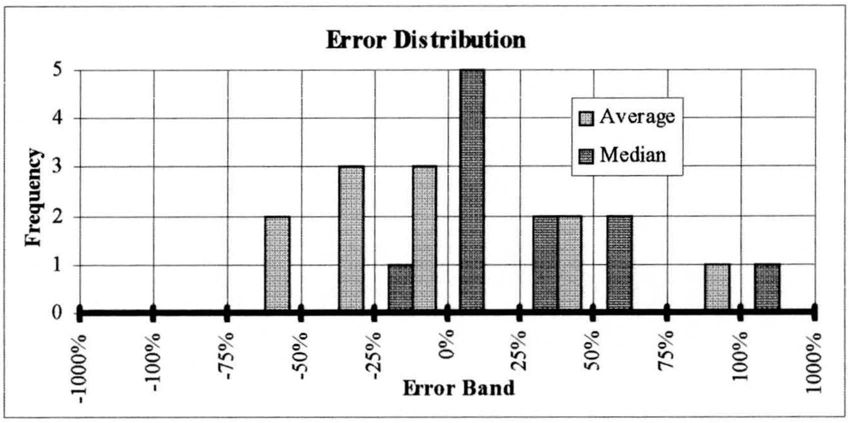

Figure 3.1 Error distribution of machine set-up time

CNC Machine De-Set-up Time = 88 seconds

Definition :

Total time taken to turn off the cutting flames and move machine away from work area so that it is available for the next operation.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	44%
Cumulative error	-50%
Standard deviation the error	53%
Lower confidence limit of 90%	-33%
Upper confidence limit of 90%	33%
Reference	Appendix A.1.2 page A-III

Table 3.2 Properties of CNC machine de-set-up time

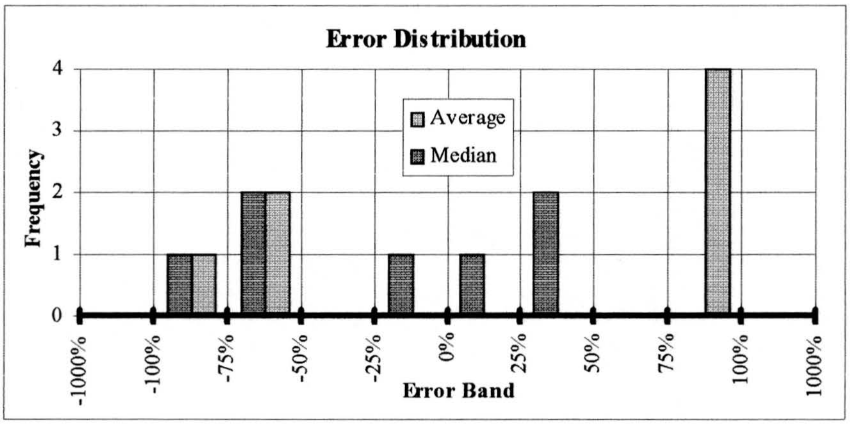

Figure 3.2 Error distribution of machine de-set-up time estimation

CNC Cutting Speed = $962*T^{-0.46}$ mm per minute with T in [mm] and $8 \leq T \leq 200$

Definition:

The CNC cutting time is the total cutting length divided by the cutting speed for a specified plate thickness.

Statistical method used to obtain formula	Power law function fitted with least squares method on median values
Correlation coefficient[2]	0.894
Valid range for formula	$8 \leq T \leq 200$ with T in [mm]
Average absolute error	18%
Cumulative error	-4%
Standard deviation the error	23%
Lower confidence limit of 90%	-11%
Upper confidence limit of 90%	1%
Reference	Appendix A.1.3 page A-IV

Table 3.3 Properties for estimating CNC cutting time with formula

The formula for cutting speed estimation was determined by taking the respective median and average values of the recorded speeds for each plate thickness. Curves were then fitted to the median values over a series of plate thicknesses with the least squares method. Different functions were fitted to the data namely: linear line, logarithmic- and power law functions. The curve that gave the smallest error over the whole plate thickness range, was the power law function fitted on the median values. The power function will yield an infinite result when the material thickness approaches 0mm. This will not hinder the use of the equation since the cut-off point for the CNC flame profile cutting process is ±4mm (if used outside the limits of the equation). Estimating cutting speeds for material thicknesses above 200mm will also not yield a negative result. The power function also coincides with the trend suggested by Affrox [1996] over the range 8 to 200mm.

[2] Correlation coefficients close to 1 indicates good correlation while coefficients close to 0 indicates no correlation. See Appendix-H.

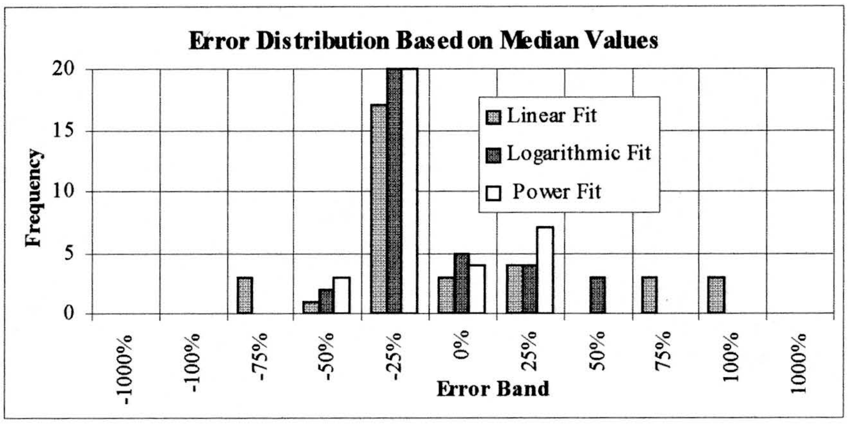

Figure 3.3 Error distribution for cutting time estimation

Piercing Time = 1.95·T+14 seconds with T in [mm] and 8≤T≤200

Definition:

Total time taken by cutting nozzle to make a hole in the material and to cut a small square around the roughly pierced hole in order to obtain a clean cutting edge.

Statistical method used to obtain formula	Straight line fitted with least squares method on median values
Correlation coefficient	0.962
Valid range for formula	8≤T≤200 with T in [mm]
Average absolute error	19%
Cumulative error	-3%
Standard deviation the error	26%
Lower confidence limit of 90%	-9%
Upper confidence limit of 90%	7%
Reference	Appendix A.1.4 page A-VIII

Table 3.4 Properties for estimating piercing time with formula

The piercing time estimation formula was determined by taking the respective median of the recorded piercing times for each plate thickness. A linear curve was then fitted, with the least squares method, through these median values for a series of different plate thicknesses.

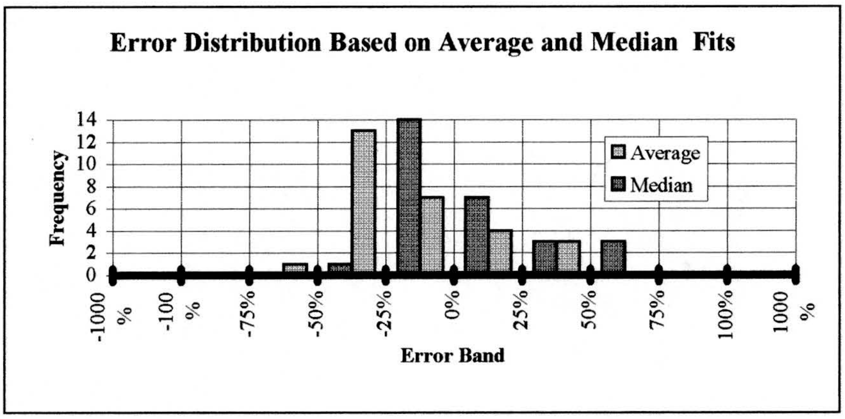

Figure 3.4 Error distribution of piercing time estimation

The deviation from a normal distribution can be attributed to the piercing of thinner plate material that did not require the cutting of a hole to obtain a clean cutting edge.

Material Set-up Time = 253 seconds

Definition:

Total time taken to move material from storage bay to machine bed to align the plate material with the machine bed.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	34%
Cumulative error	-37%
Standard deviation the error	46%
Lower confidence limit of 90%	-36%
Upper confidence limit of 90%	40%
Reference	Appendix A.1.5 page A-X

Table 3.5 Properties of material set-up time

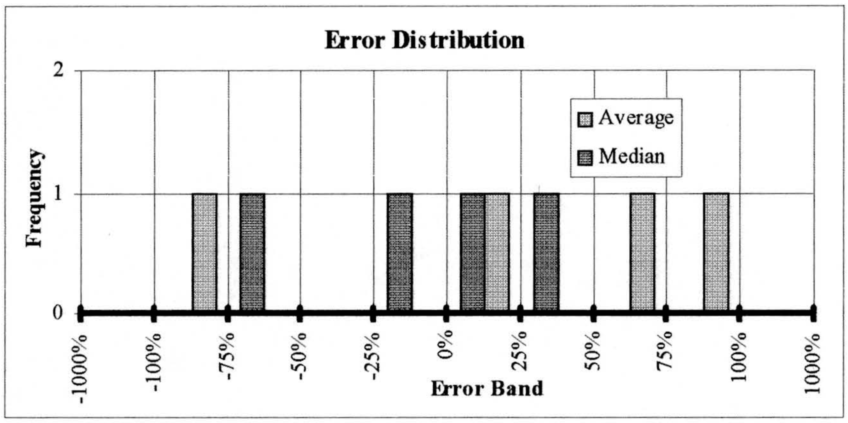

Figure 3.5 Error distribution of material set-up time estimation

Part Removal Time = 40 seconds

Definition:

Time taken to move a part (already connected to crane) from the machine bed to the grinding tables.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	31%
Cumulative error	-1%
Standard deviation the error	38%
Lower confidence limit of 90%	-10%
Upper confidence limit of 90%	10%
Reference	Appendix A.1.6 page A-XI

Table 3.6 Properties of part removal time

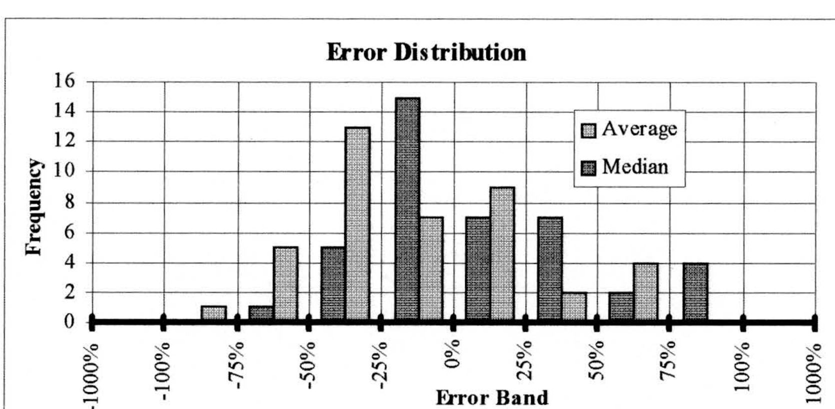

Figure 3.6 Error distribution of part removal time estimation

Part Connecting Time = 25 seconds

Definition:

Total time taken to connect electro magnet to part and untangle part if necessary.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	86%
Cumulative error	-20%
Standard deviation the error	125%
Lower confidence limit of 90%	-34%
Upper confidence limit of 90%	34%
Reference	Appendix A.1.8 page A-XII

Table 3.7 Properties of part connecting time

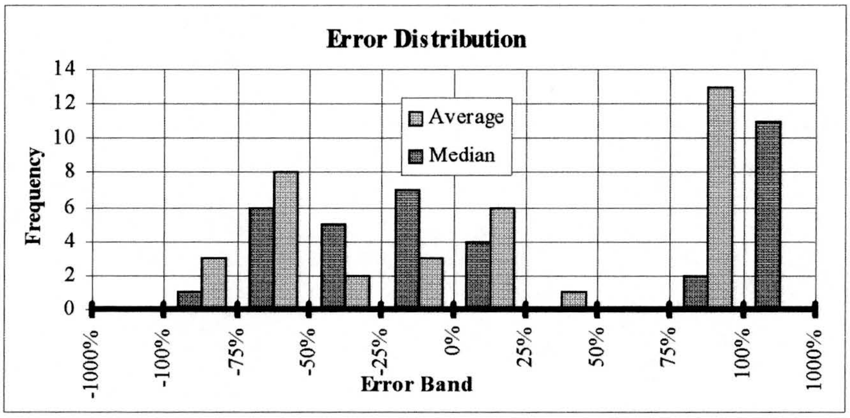

Figure 3.7 Error distribution of part connecting time estimation

The increase in frequency to the right of the graph can be attributed to parts that did not tangle at all.

Return Time = 27 seconds

Definition:

Total time taken to move overhead crane from grinding table back to the machine bed.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	23%
Cumulative error	-13%
Standard deviation the error	30%
Lower confidence limit of 90%	-8%
Upper confidence limit of 90%	8%
Reference	Appendix A.1.8 page A-XV

Table 3.8 Properties of return time

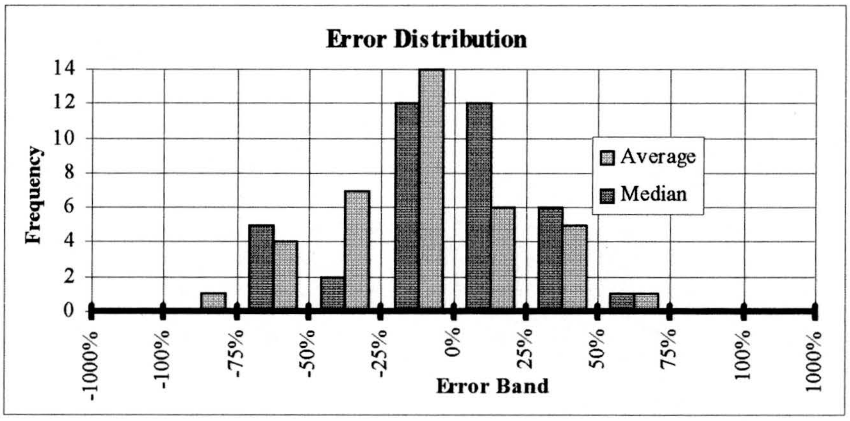

Figure 3.8 Error distribution of return time estimation

Scrap Removal Time = 73 seconds

Definition:

Total time taken to remove scrap material from the machine bed to scrap bin.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	14%
Cumulative error	-8%
Standard deviation the error	23%
Lower confidence limit of 90%	-22%
Upper confidence limit of 90%	22%
Reference	Appendix A.1.9 page A-XV

Table 3.9 Properties of scrap removal time element

Too few data points were recorded to obtain a true representative error distribution.

Pierced Hole Cleaning Time = 11 seconds per hole

Definition:

Total time taken to remove all solidified metal around the pierced hole with a crowbar.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	27%
Cumulative error	-47%
Standard deviation the error	45%
Lower confidence limit of 90%	-43%
Upper confidence limit of 90%	43%
Reference	Appendix A.1.10 page A-XVI

Table 3.10 Properties of pierced hole cleaning time element

Too few data points were recorded to obtain a true representative error distribution.

Many of the time elements presented here cannot be estimated very accurately. The estimation that has the greatest influence on the models accuracy is the profiling speed estimation which is used to estimate the profiling time element. Therefore, the effect of a small time element with a large error will not be as significant.

3.2.3. ***Time Estimation for the CNC Profiling Process***

The time estimation model uses a combination of the above mentioned constants and equations to obtain the total CNC flame profile cutting time. The time estimation formulas given in Table 3.12 were derived from the process flow diagram, Figure 3.9. Table 3.11 summarises the occurrence of each time element.

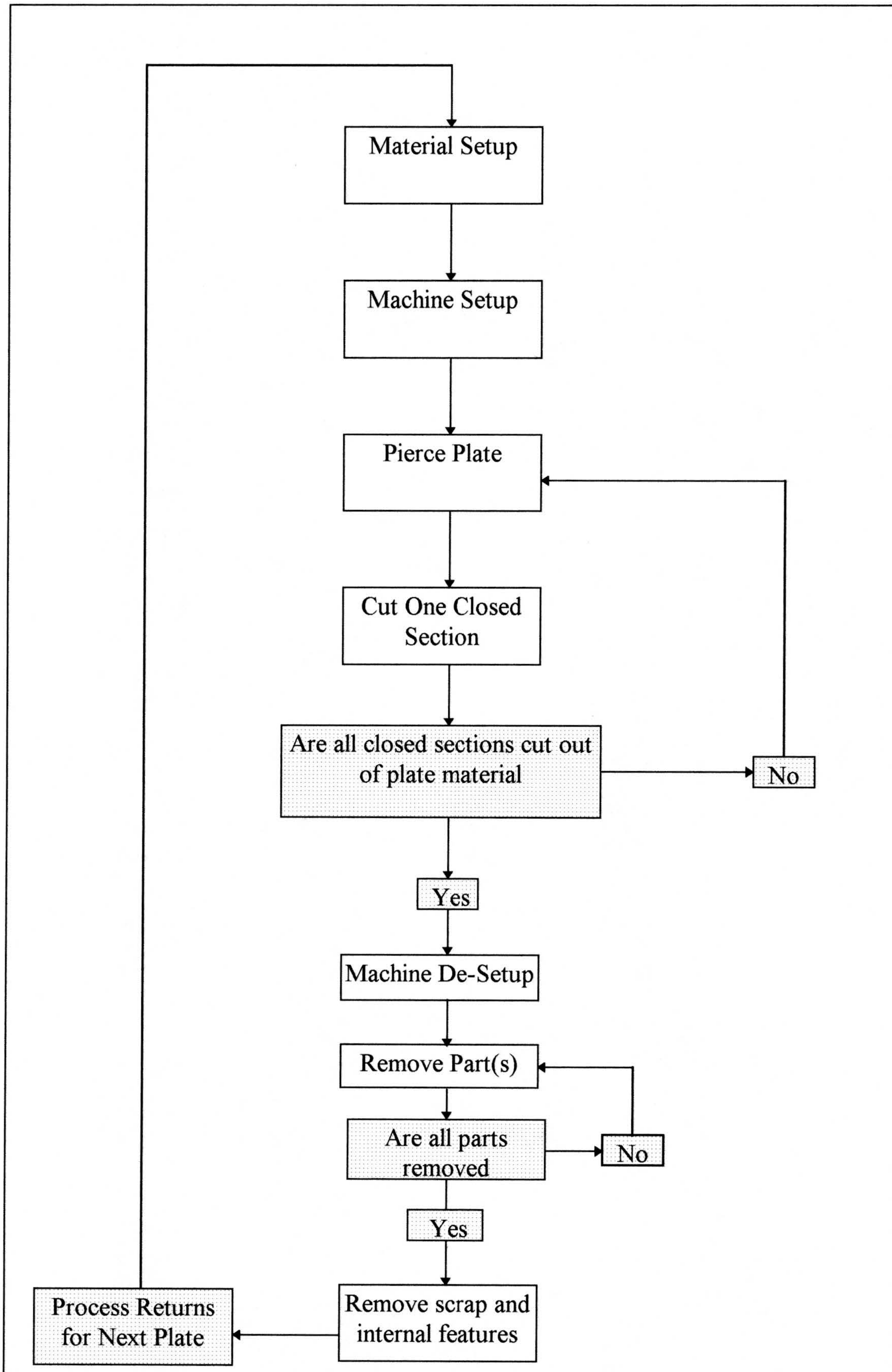

Figure 3.9 Process flow diagram for CNC profiling

Element Name	**Occurrence**
CNC Machine Set-up Time	Per batch (plate)
CNC Machine De-Set-up Time	Per batch (plate)
CNC Cutting Time	Per part and per internal feature
Piercing Time	Per part and per internal feature
Material Set-up Time	Per batch (plate)
Part Removal Time	Per Part
Part Connecting Time	Per Part
Return Time	Per part, per internal feature and per scrap section (1)
Scrap Removal Time	Per internal feature and per scrap section (1)
Pierce Hole Cleaning Time	Per part and per internal feature if material thicker than 30 mm

Table 3.11 Occurrence of CNC flame profile cutting time elements

CNC Process Times			
Description	**Formula**	**Unit**	**Variable Declaration**
Cutting time	$\frac{L}{967 \cdot T^{-0.46}} \cdot 60$	s	L : Length to be cut on plate material [mm] T : Thickness of plate material [mm] $8 \leq T \leq 200$
Piercing time	$(1.95 \cdot T + 14) \cdot (N + ITF)$	s	N : Number of parts on plate ITF : Number of internal features on plate T : Thickness of plate material [mm] $8 \leq T \leq 200$
Total set-up time	$600 + 253 + 11 \cdot (N + ITF) \cdot T_c$	s	T_c=1 if plate thicker than 30mm else T_c=0
Total de-set-up time	$188 + 92 \cdot N + 125 \cdot ITF$	s	

Table 3.12 CNC flame profile cutting time estimation formulas

3.3. Time Estimation for Burr Removal of CNC Profiled Parts

The CNC flame profile cutting process leaves a burr (slag) on the part edges. The burr must be removed before the part can move to the next stage of production. These burrs are found on both sides of the part and are removed with a grinder, normally an air grinder in the plant where data was collected. Burr removal is necessary because it makes handling easier, produces a clean surface required for welding and eases marking operations which may occur during later stages of production.

The grinding time per disk, for burr removal grinding, is much longer than for other grinding operations. The grinding disk requirements were therefore omitted from the study. The burr removal process is broken down into the following time elements according to the process flow diagram, Figure 3.15:

1. Grinding set-up time (there are two set-up times per part for burr removal grinding, one for each side).
2. Grinding time.
3. Grinding de-set-up time (there are two de-set-up times per part for burr removal grinding, one for each side).
4. Part handling time (turning alone because the part is placed on the grinding table directly after it has been removed from the CNC machine bed).

3.3.1. *Constants for Burr Removal Grinding*

The terms and constants determined from the time study are as follows:

Grinder Set-up = 30 seconds

Definition:

Total time taken by operator to put on eye and hearing protection, grasp grinder and to commence grinding.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	65%
Cumulative error	-9%
Standard deviation the error	18%
Lower confidence limit of 90%	-28%
Upper confidence limit of 90%	36%
Reference	Appendix B.1.1 page B-II

Table 3.13 Properties of grinder set-up time element

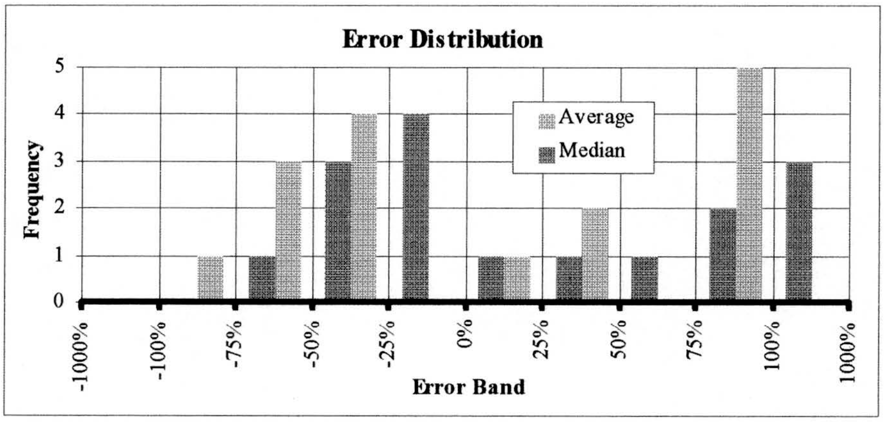

Figure 3.10 Error distribution for grinding set-up time estimation

The frequency increase in error band 75% to 1000% can be attributed to easy grinder set-up times whenever accessibility were very good.

Grinder De-Set-up = 22 seconds

Definition:

> Total time taken by operator to switch grinder off, put grinder down and remove eye and hearing protection.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	68%
Cumulative error	-11%
Standard deviation the error	88%
Lower confidence limit of 90%	-44%
Upper confidence limit of 90%	44%
Reference	Appendix B.1.2 page B-III

Table 3.14 Properties of grinder de-set-up time element

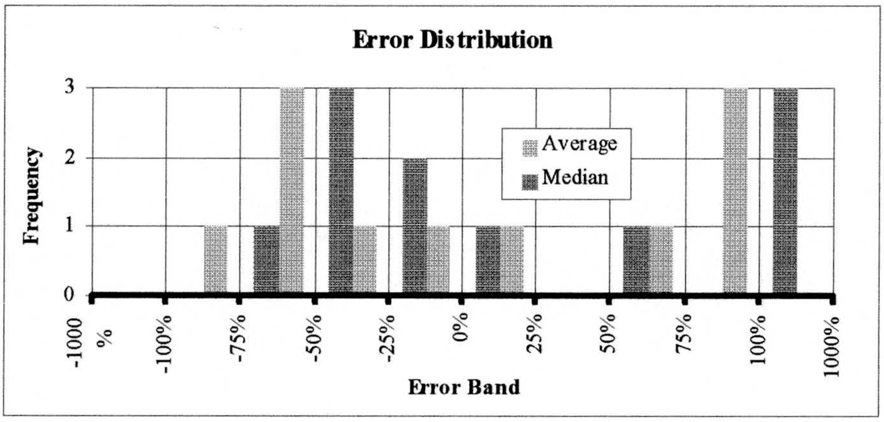

Figure 3.11 Error distribution for grinder de-set-up time estimation

Burr Removal Grinding Speed = 7041 mm per minute

Definition:

The burr removal grinding time is defined as the total grinding length on the part divided by the grinding speed.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	24%
Cumulative error	1%
Standard deviation the error	34%
Lower confidence limit of 90%	-18%
Upper confidence limit of 90%	18%
Reference	Appendix B.1.3 page B-IV

Table 3.15 Properties of burr removal time estimation

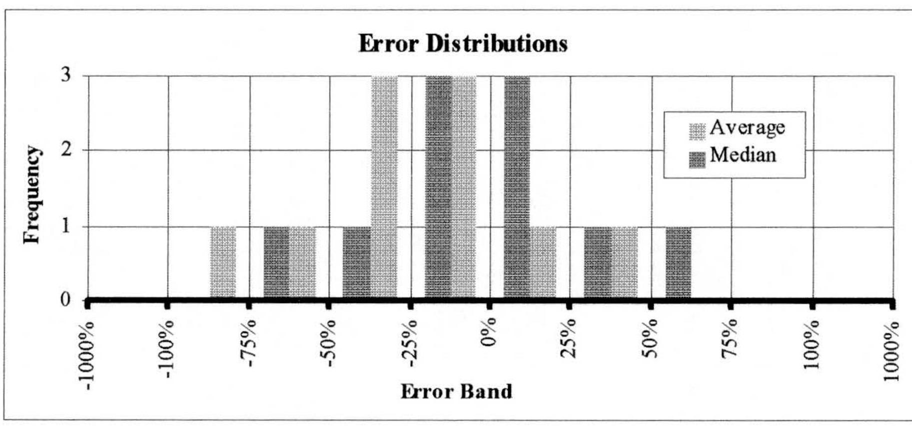

Figure 3.12 Error distribution for grinding time estimation

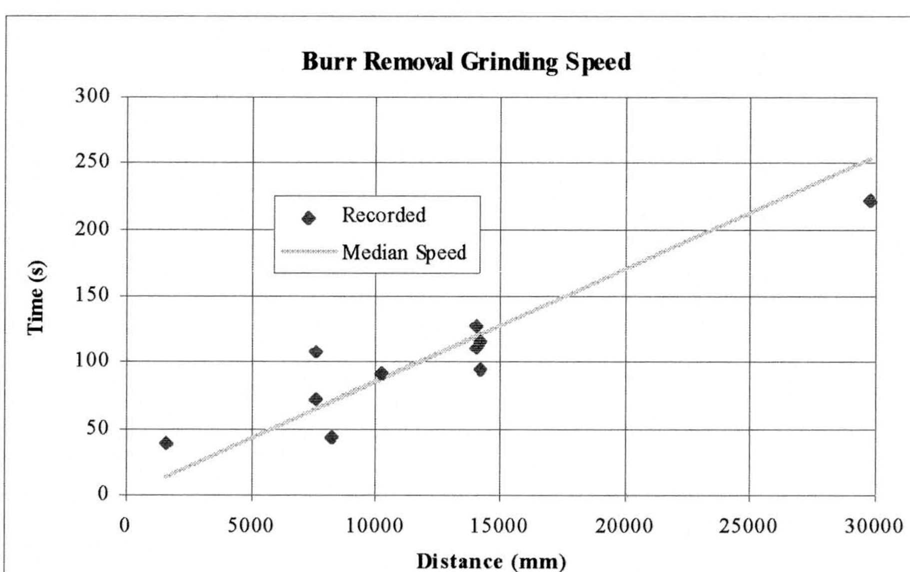

Figure 3.13 Recored grinding time data plot

3.3.2. ***Constant for Handling Time***

Part Turn Time = 196 seconds

Definition:

The total time taken to turn a part around.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	85%
Cumulative error	-18%
Standard deviation the error	102%
Lower confidence limit of 90%	-27%
Upper confidence limit of 90%	27%
Reference	Appendix E.2.5 page E-XII

Table 3.16 Properties of part turn time element

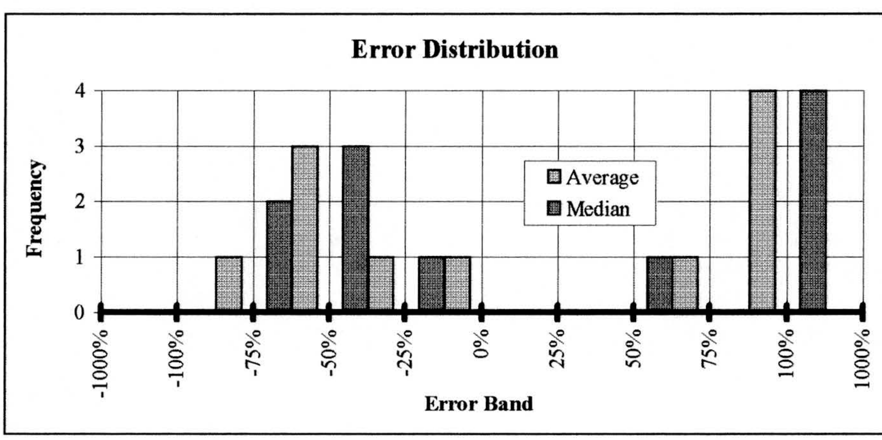

Figure 3.14 Error distribution for turn time estimation

The frequency gap from error band 0% to 50% can be attributed to parts that could be turned with the hand by two persons and incurred no crane handling time.

3.3.3. ***Procedure for Calculating the Burr Removal Process Time***

The time estimation model uses a combination of the above mentioned constants to estimate the grinding time required for burr removal. The time estimation formulas given in Table 3.18 estimates the required grinding time per part and were constructed from the process flow diagram, Figure 3.15. Table 3.17 summarises the occurrence of the time elements.

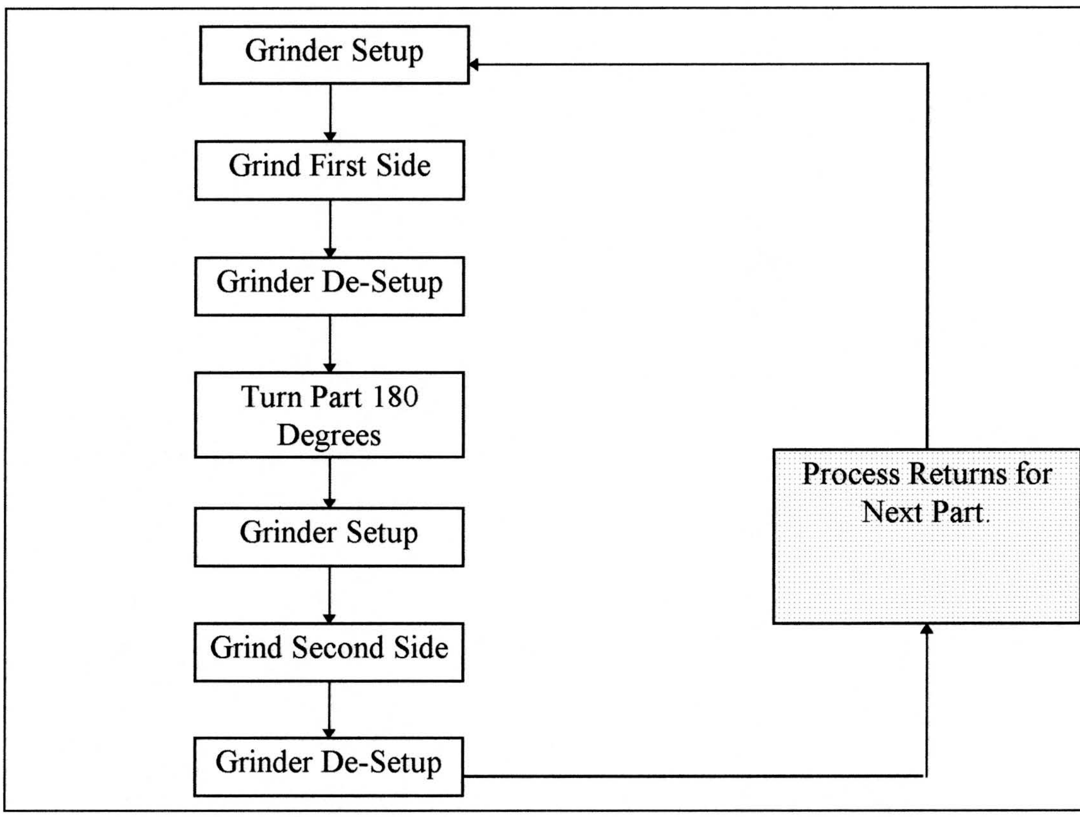

Figure 3.15 Process flow diagram for burr removal grinding

Element	Occurrence
Grinder Set-up	Per part side
Grinder De-Set-up	Per part side
Burr Removal Grinding Time	Per part side
Part Turn Time	Per part

Table 3.17 Occurrence of burr removal time elements

CNC Flame Profile Cutting Secondary Process Times			
Description	**Formula**	**Unit**	**Variable Declaration**
Grinding time	$\frac{2 \cdot L}{7041} \cdot 60$	s	L : Total profiled length on plate material [mm]
Set-up/De-set-up time	$104 \cdot N$	s	N : Number on parts on plate material
Handling time	$196 \cdot N$	s	N : Number on parts on plate material

Table 3.18 Burr removal time estimation formulas

4. Weld Joint Preparation Time Estimation

4.1. Overview of Joint Preparation

Edge preparation of parts includes the chamfering of plate edges to ensure good welding accessibility. The preparation needed primarily depends on the penetration depth that can be achieved with the welding process used and the plate thickness. The specification of weld joint preparations automatically fixes the amount of weld metal and welding time required. The designer must, therefore, specify these preparations as economically as possible with regards to the bevel dimensions [P&H 1998].

4.1.1. *The Designer's Influence*

The designer can minimise the volume of metal required for a specific weld joint design. This can be achieved by considering the following [Feder,1993]:

1. Design joints that are compatible with the welding process to be used. If possible try to design for continuous welding processes. The designer should ensure that the weld joint is accessible. Good accessibility will make the welding operators work easier and hence improve his operating factor. The designer should make allowances, when designing a weld joint for continuous processes, for torch accessibility. This will affect the shielding gas flow (shielding quality) and the electrode stick-out (welding penetration).
2. The designer should make use of double fillet weld sections instead of single fillet weld sections. This will reduce the leg length of the weld section, thereby halving the amount of weld metal required whilst still maintaining the same structural strength and reducing distortion.
3. Use double-V weld preparations instead of single-V preparations. This will reduce the amount of weld metal required and reduce the possibility of distortion.
4. Use small included angles. A reduction of 50% in included angle can halve

the amount of weld metal required.

5. Use large root faces for welding processes with deep penetration capabilities, such as flux core arc welding.
6. Use butt welds with a backing bar to avoid back gouging. Gouging should only be specified if absolutely necessary.
7. Use 480 MPa minimum tensile strength filler metal to minimise fillet sizes.
8. When joining two plates, bevel only one. This will reduce the amount of weld metal required.

Keubler [1989] suggests that designer should simplify the design as much as possible and standardise the components or sub-assemblies of the structure. This will encourage jigging and the use of mechanised welding for larger production volumes. It will also decrease the set-up time of welding and increase operator efficiency by making operators more confident with the welding procedure for the assembly. This is a somewhat indirect approach of reducing welding costs.

Salter [1989] suggests that designers should do trade-off studies for using thinner plate material with higher tensile strength requiring no joint preparation, versus thicker plates with low tensile strength. The weight of electrode saved by using thinner, high tensile strength plate material may very well be offset by the preheating and stiffener preparation requirements (which increases the risk of distortion), than extra weld material required when using thicker plate material with a lower tensile strength.

Edge preparation can be done in various ways, from machining to manual bevelling with a cutting torch. Edge preparation can even be formed as an integral part of CNC profiling by using an automatic rotate-able head with more than one cutting nozzle, one to cut the plate and the other to cut the bevel side. This will completely eliminate the bevelling operation.

4.1.2. ***Manual and Mechanised Bevelling***

The most common methods to bevel part edges are:

1. The mechanised bevelling procedure.
2. The manual bevelling procedure.

With mechanised bevelling, a portable machine with a cutting torch and a guide is positioned onto the part edge. Cutting of the bevelled section is controlled automatically under the operators supervision. With manual bevelling, the operator cuts a bevel with a hand held torch.

Both of these processes have their advantages and disadvantages.

Advantages of mechanised bevelling :

- Cuts a clean bevel on straight edges which requires less cleaning afterwards than would be required for manual bevelled edges.
- The portable machine requires less repositioning for long bevel edges than manual bevelled edges. With manual bevelling the operator has to reposition himself after approximately every 260mm. With mechanised bevelling the repositioning length is about 1270 mm, depending on the length of the guide.
- The process is easy to use and does not require special hand skills or specialised training.

Advantages of manual bevelling :

- The set-up time for a hand held torch is faster than that for mechanised bevelling.
- Bevelling can be performed in hard to reach places and it does not require the part to lie flat. The manual bevelling process is more flexible than mechanised bevelling.
- The process is ideal for trimming of parts that have fit-up problems.
- Manual bevelling is ideally suited for short bevel lengths.

- The cutting speed is faster than the cutting speed for mechanised bevelling.

The decision to bevel manually or with the mechanised process depends mainly on the geometry of the plate and the length to be bevelled. The decision to use either one of these processes is greatly influenced by the clean grinding that has to take place afterwards. The clean grinding speed for mechanised bevelled edges is approximately 150% faster than the clean grinding speed of manual bevelled edges. Designers and production personnel can, therefore, use bevelling time estimation models to do trade-off studies between the two processes to identify the most economical one for a specific joint preparation.

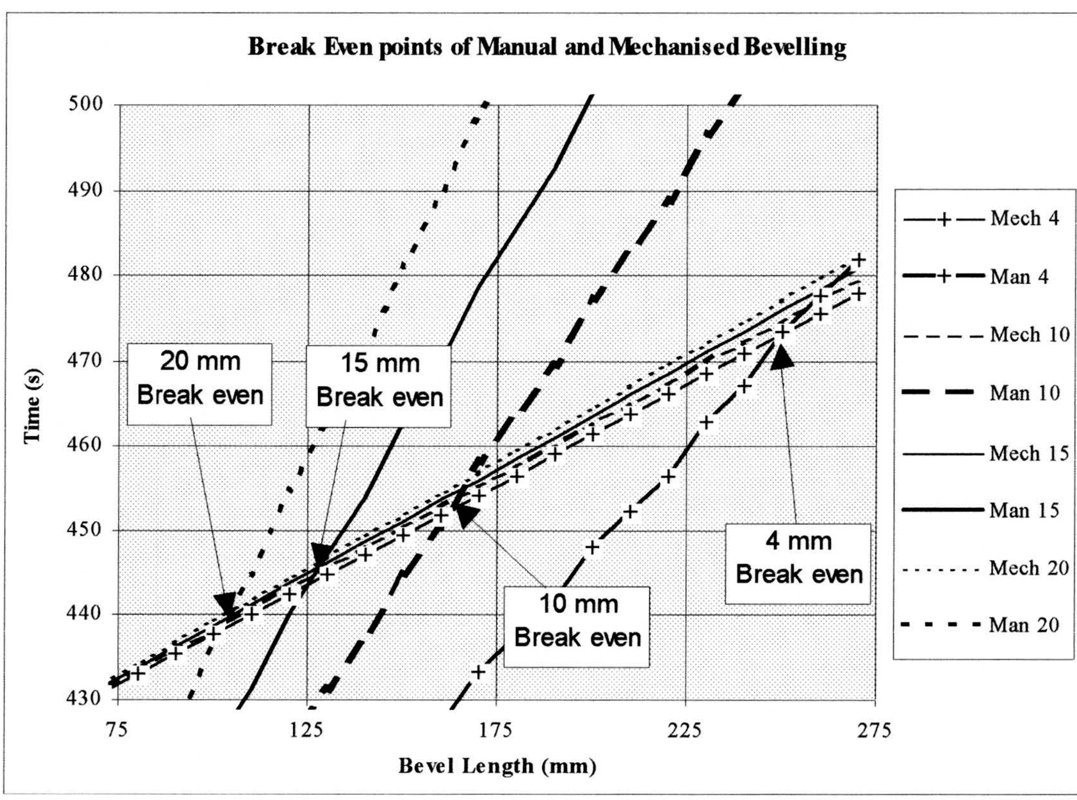

Figure 4.1 Break even point between manual and mechanised bevelling

Figure 4.1 shows the break even points between the manual and mechanised bevelling processes, including grinding for different bevel sizes. It was determined with the time estimation models presented within this thesis.

4.2. **Time Estimation for the Bevelling Process**

4.2.1. ***Model Construction***

The total time required for manual and mechanised bevelling is broken down into smaller time elements. These time elements are related to specific operator tasks and machine cycle times. Each element is then calculated and combined in a proper manner with the other time elements according to the process flow diagrams.

The cutting speed suggested by Afrox [1996] and Cary [1992] gives a relation between the bevelling speed and the bevel size. Analysis of the time study data, however, showed no correlation between the bevelling speed and the bevel size. The recorded data showed that the bevelling speed differed from one bevelling operator to another, even if the size of the bevel is the same. This was evident for the manual and mechanised bevelling procedures.

4.2.2. ***Mechanised Bevelling Time Estimation***

The process flow diagram for mechanised bevelling is given in Appendix C.

The time study showed that the total mechanised bevelling process time can be broken down into the following time elements :

1. Cutting time.
2. Total set-up and de-set-up time.
3. Re-set-up time.
4. Handling time.
5. Measuring and marking time.

These time elements can be calculated and summed together (according to the process flow diagram) to obtain the total mechanised bevelling time.

4.2.3. *Constants for Mechanised Bevelling*

The time study data was used to obtain constants for the above mentioned time elements.

Mechanised Bevel Cutting Time = 0.223·L+27 seconds

Definition:

Total time taken to cut a bevel.

Statistical method used to obtain constant	Robust data analysis
Valid range for formula	140≤L≤2451 with L in [mm]
Average absolute error	13%
Cumulative error	-6%
Standard deviation the error	16%
Lower confidence limit of 90%	-6%
Upper confidence limit of 90%	4%
Reference	Appendix C.1.3 page C-IV

Table 4.1 Properties of mechanised bevel cutting time element

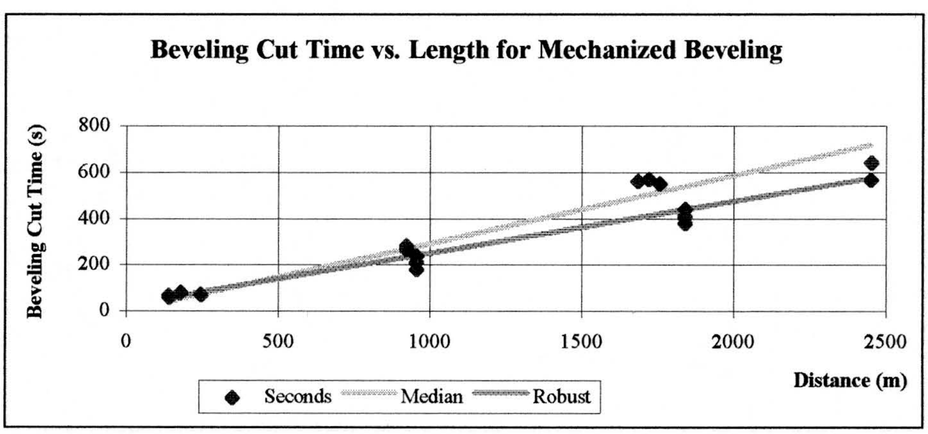

Figure 4.2 Bevel cut time vs. length for mechanised

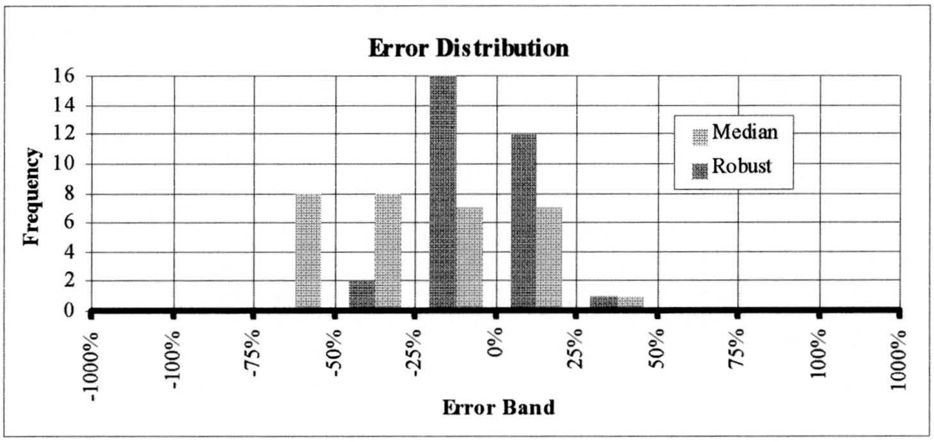

Figure 4.3 Error distribution for mechanised bevelling cutting time estimation

Mechanised Bevel Set-up Time = 92 seconds

Definition:

Total time taken by operator to position guiding track and bevelling machine, igniting and tuning the cutting flame and commence cutting.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	31%
Cumulative error	-20%
Standard deviation the error	43%
Lower confidence limit of 90%	-17%
Upper confidence limit of 90%	17%
Reference	Appendix C.1.1 page C-III

Table 4.2 Properties of mechanised bevel set-up time element

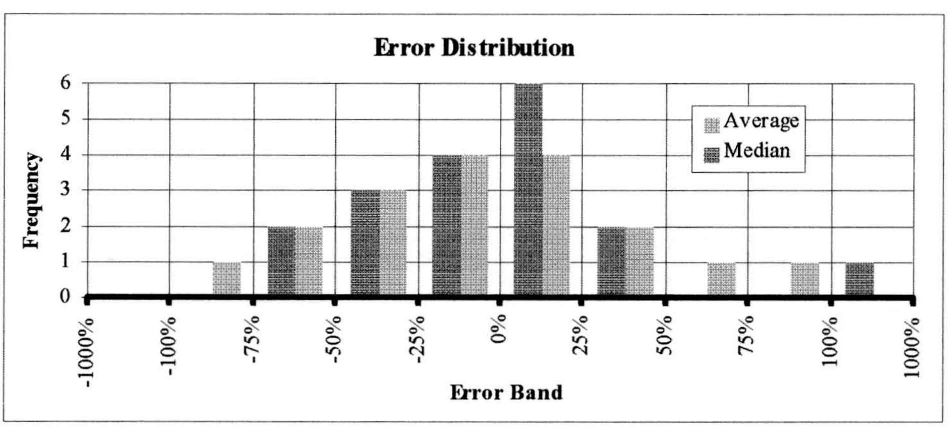

Figure 4.4 Error distribution for set-up time estimation

Mechanised Bevel De-Set-up Time = 14 seconds

Definition:

Total time taken by operator to turn cutting flame off and to remove bevelling machine and guiding track from part.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	68%
Cumulative error	-22%
Standard deviation the error	83%
Lower confidence limit of 90%	-44%
Upper confidence limit of 90%	42%
Reference	Appendix C.1.2 page C-III

Table 4.3 Properties of mechanised bevel de-set-up time element

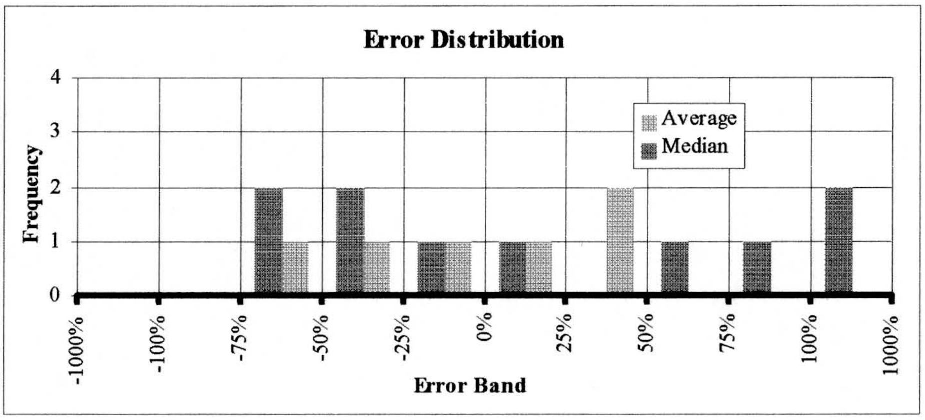

Figure 4.5 Error distribution for de-set-up time estimation

The wide frequency spread can be attributed to operator related factors.

Mechanised Bevel Burr Cleaning Time = 0.01·L+18 seconds

Definition:

Total time taken by operator to remove cutting slag from bevel edge.

Statistical method used to obtain formula	Robust data analysis
Valid range for formula	140≤L2451 with L in [mm]
Average absolute error	36%
Cumulative error	-22%
Standard deviation the error	43%
Lower confidence limit of 90%	-6%
Upper confidence limit of 90%	32%
Reference	Appendix C.1.4 page C-V

Table 4.4 Properties of mechanised bevel burr cleaning time

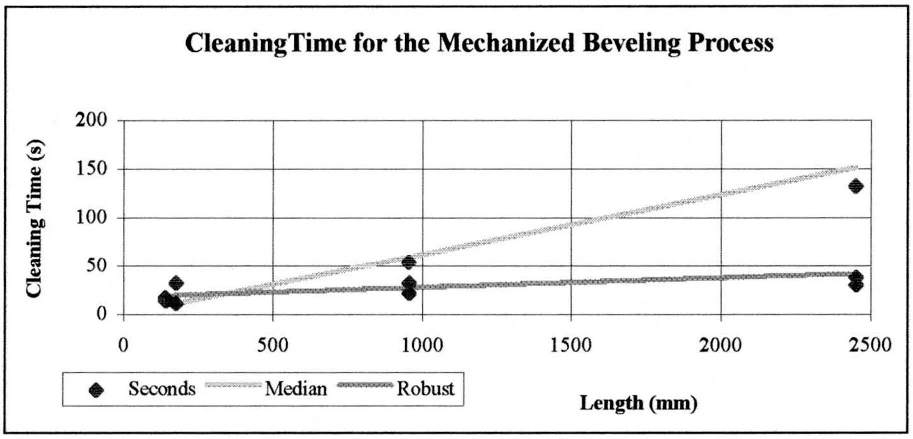

Figure 4.6 Cleaning time vs. length for mechanised bevelled edges

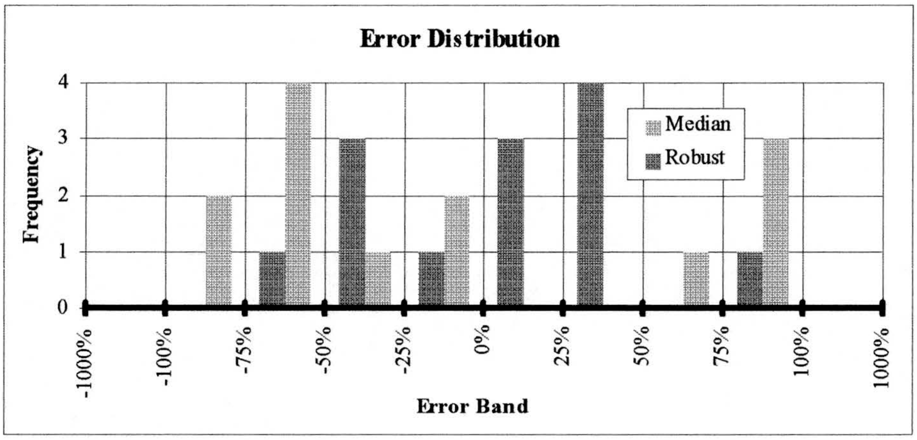

Figure 4.7 Error distribution for burr cleaning time estimation

Mechanised Bevel Re-Set-up Time = 63 seconds

Definition:

Total time taken by operator to move machine and track to new position to continue bevel cutting for long bevel sections.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	23%
Cumulative error	-2%
Standard deviation the error	28%
Lower confidence limit of 90%	-25%
Upper confidence limit of 90%	21%
Reference	Appendix C.1.5 page C-VII

Table 4.5 Properties of mechanised bevel re-set-up time element

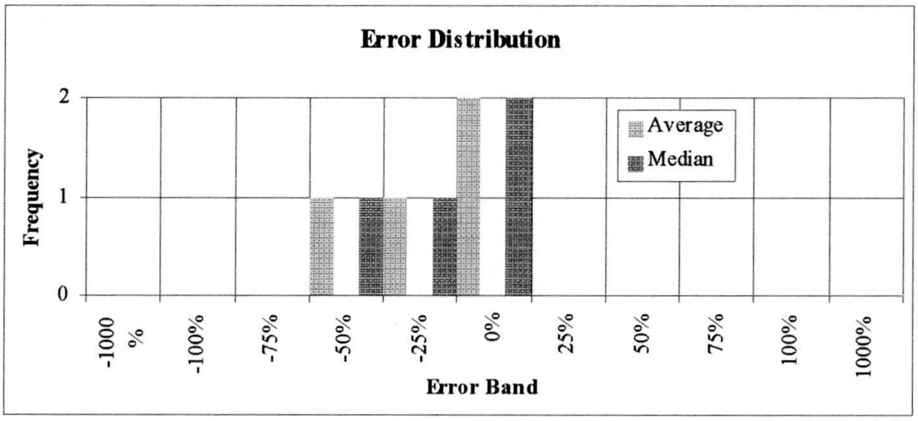

Figure 4.8 Error distribution for re-set-up time estimation

Marking Time = 0.031·L·2+ 16·NL seconds

Definition:

Total time taken by operator to measure and make small marks and draw lines with the aid of these marks on a part.

Statistical method used to obtain constant	Multiple linear regression
Valid range for formula	65≤L≤3803 with L in [mm] and
Average absolute error	43%
Cumulative error	0%
Standard deviation the error	47%
Lower confidence limit of 90%	19%
Upper confidence limit of 90%	19%
Reference	Appendix C.2 page C-VII

Table 4.6 Properties of marking time element

The number of marking lines (NL) and the total length of bevel (L) were taken as variables. Average and median making times were also analysed. The constants, of the multiple linear regression, were then adjusted with Excel Solver to minimise the average absolute error. The equation (multiple linear regression) as shown above gave the closest time estimation with reasonable errors.

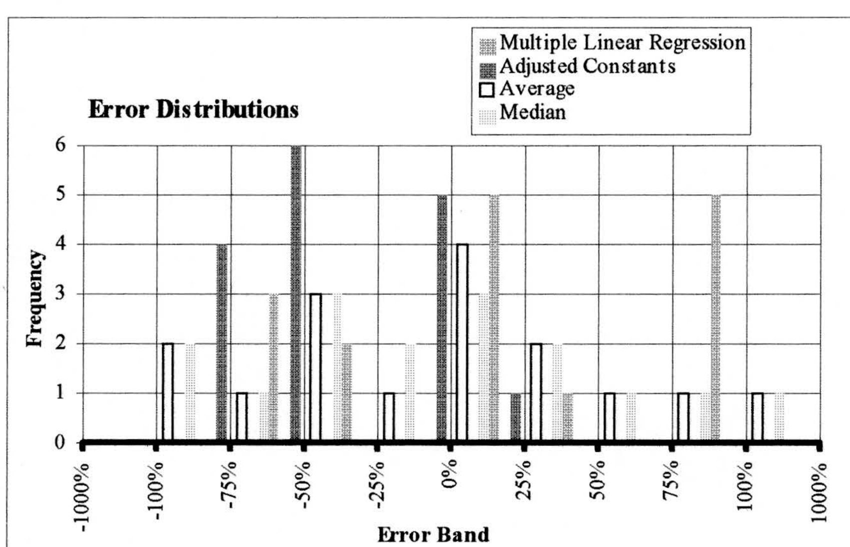

Figure 4.9 Error distribution for measuring and marking time estimation

4.2.4. ***Constants for Handling Time***

Part Connecting Time with Overhead Crane = 37 seconds.

Definition:

Total time taken by operator to connect a part with chain and hook to an overhead crane.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	76%
Cumulative error	-24%
Standard deviation the error	110%
Lower confidence limit of 90%	-36%
Upper confidence limit of 90%	36%
Reference	Appendix E.2.1 page E-VII

Table 4.7 Properties of part connecting time element

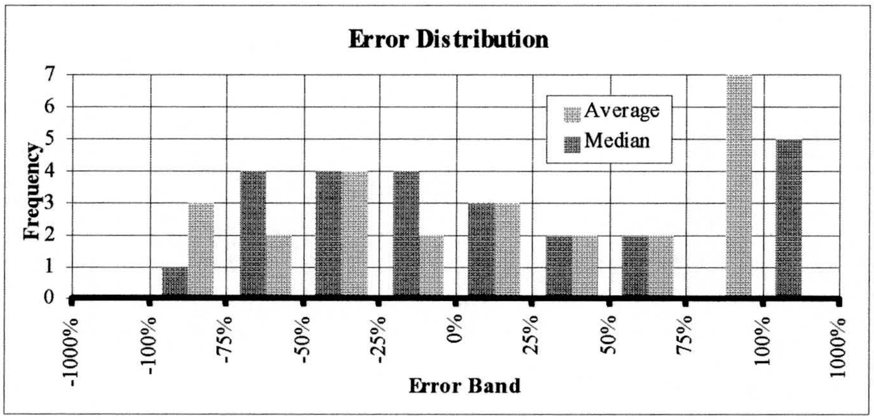

Figure 4.10 Error distribution for connecting time estimation

The increase in the distribution to the right of the graph can be attributed to parts that were easily connectable such as parts with holes.

Part Disconnecting Time With Overhead Crane = 15 seconds

Definition:

Total time taken by operator to disconnect chain and hook from part and to remove the crane to a safe position nearby.

Statistical method used to obtain constant	Median of recorded times
Average absolute error	103%
Cumulative error	-28%
Standard deviation the error	151%
Lower confidence limit of 90%	-52%
Upper confidence limit of 90%	52%
Reference	Appendix E.2.2 page E-VIII

Table 4.8 Properties of part disconnecting time element

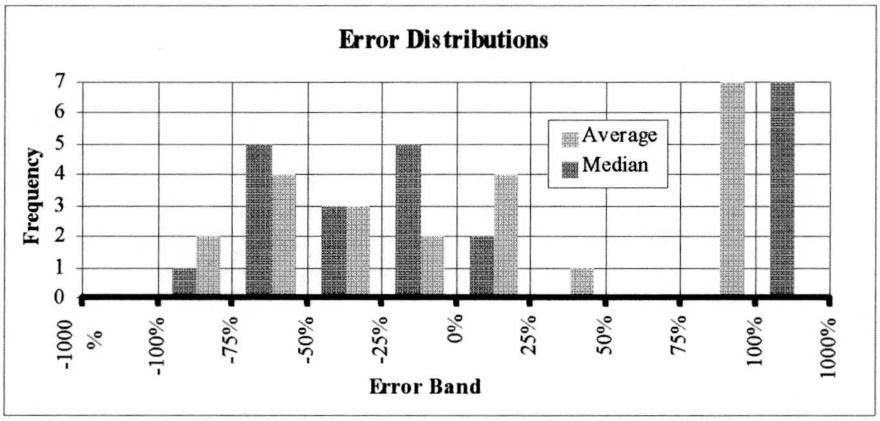

Figure 4.11 Error distribution for disconnecting time estimation

Part Moving Time With Crane = 2.2·D+42 seconds

Definition:

Total time taken by operator to move part through distance D with an overhead crane.

Statistical method used to obtain constant	Robust data analysis
Valid range for formula	2≤D≤71 with D in [m]
Average absolute error	42%
Cumulative error	-8%
Standard deviation the error	72%
Lower confidence limit of 90%	-28%
Upper confidence limit of 90%	24%
Reference	Appendix E.2.3 page E-X

Table 4.9 Properties of part moving time element

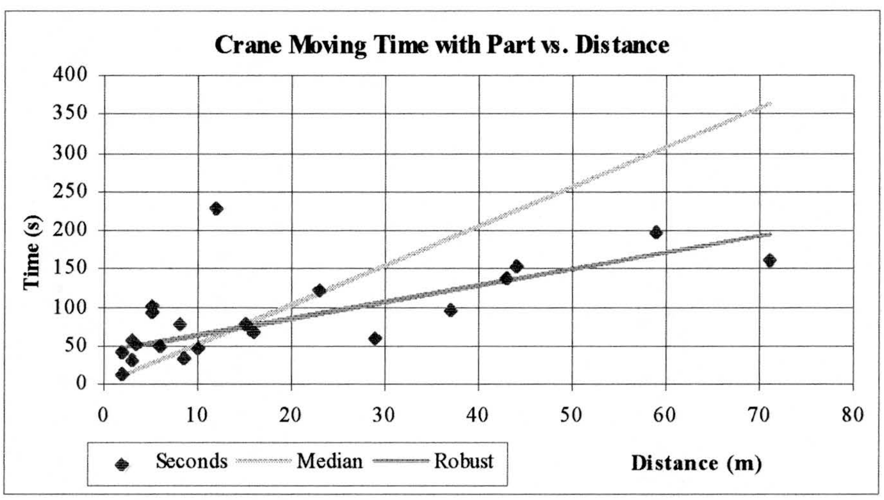

Figure 4.12 Part moving time vs. distance

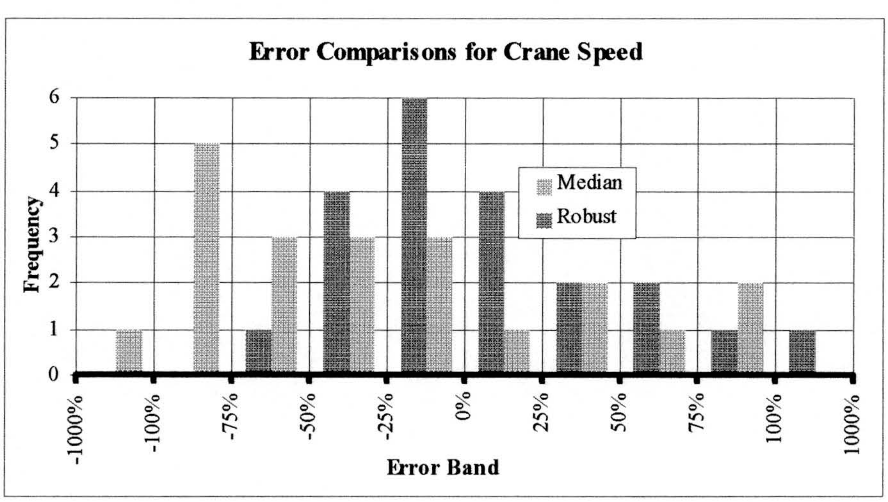

Figure 4.13 Error distribution for part moving time estimation

Crane Moving Time $=1.3 \cdot D+20$ seconds

Definition:

Total time taken by operator to move empty crane through distance D.

Statistical method used to obtain formula	Robust data analysis
Valid range for formula	$2 \leq D \leq 63$ with D in [m]
Average absolute error	37%
Cumulative error	-18%
Standard deviation the error	52%
Lower confidence limit of 90%	-17%
Upper confidence limit of 90%	13%
Reference	Appendix E.2.4 page E-XI

Table 4.10 Properties of crane moving time element

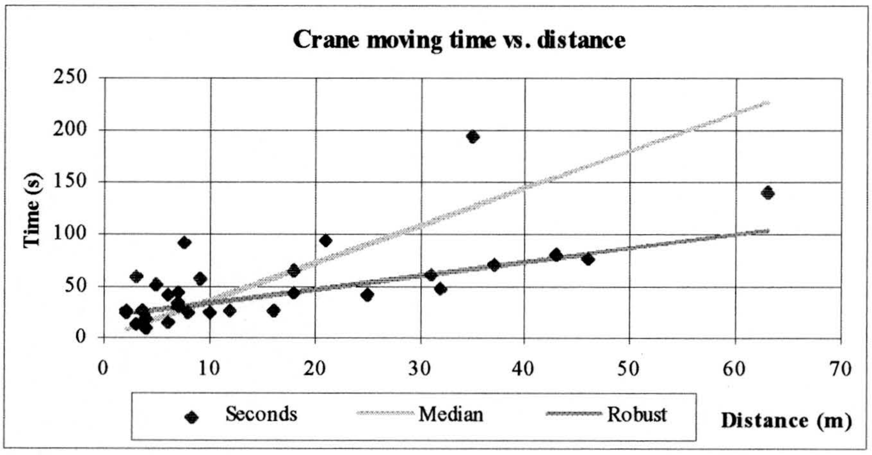

Figure 4.14 Empty crane moving time vs. distance

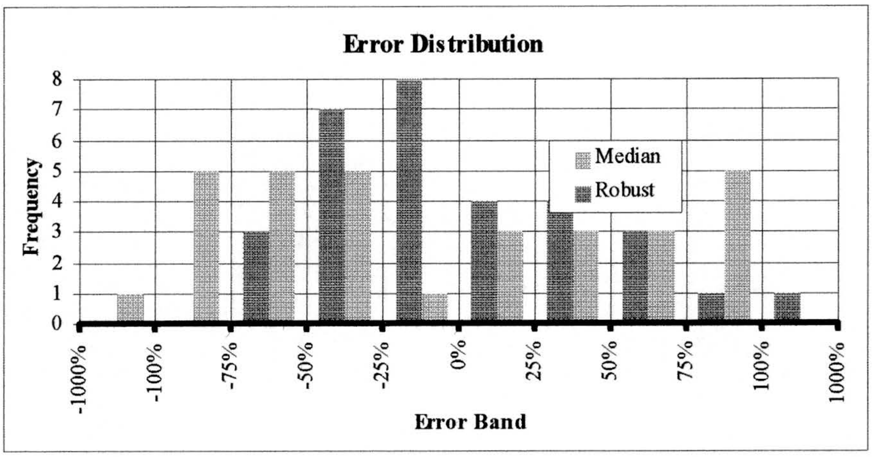

Figure 4.15 Error distribution for crane moving time estimation

4.2.5. *Time Estimation for the Mechanised Bevelling Process*

The time estimation model then uses a combination (according to the process flow diagram) of the above mentioned constants and equations to obtain the total mechanised bevelling time estimation.

Table 4.12 summarises the mechanised bevelling time estimation formulas. These formulas estimates the time per part. The formulas were constructed according the process flow diagram, Figure 4.16. Table 4.11 summarises the occurrence of the time elements.

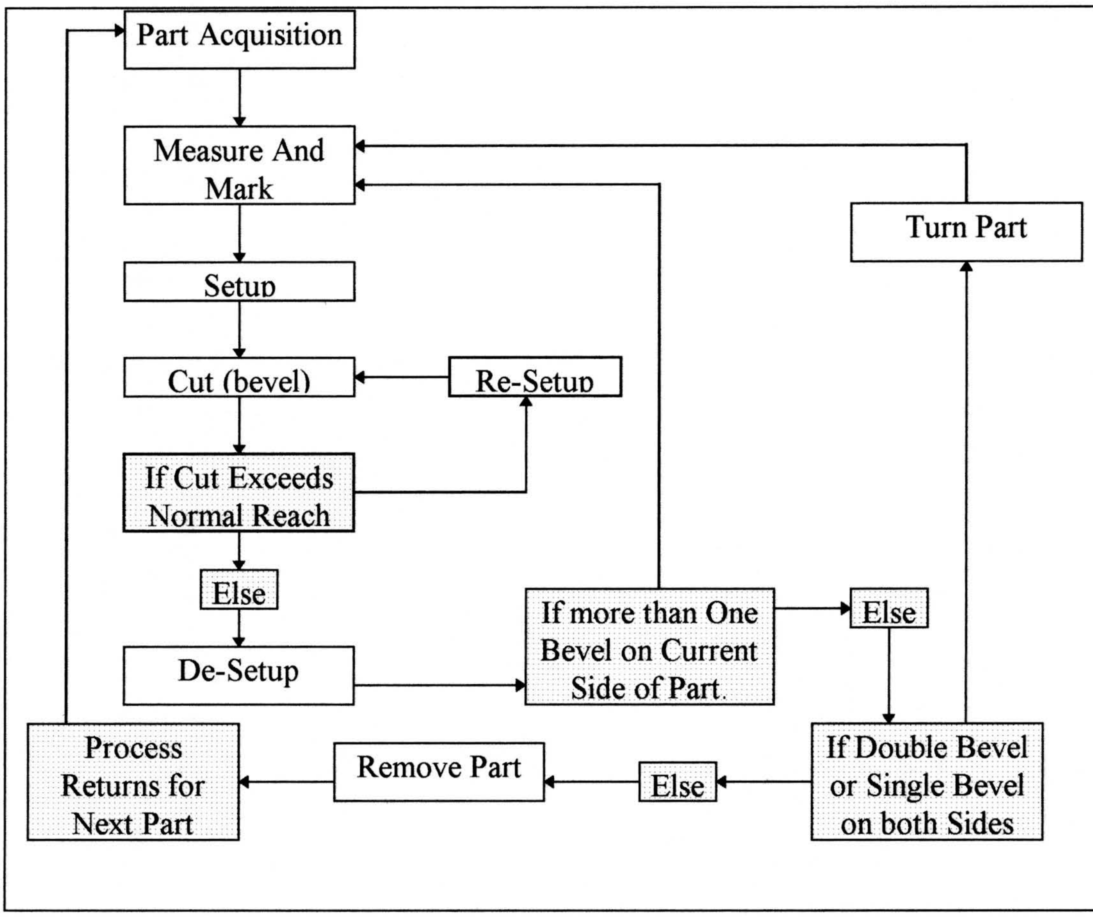

Figure 4.16 Process flow diagram for mechanised bevelling

Element	Occurrence
Mechanised Bevel Cutting Time	Per bevel and per double bevel
Mechanised Bevel Set-up Time	Per bevel and per double bevel
Mechanised Bevel De-Set-up Time	Per bevel and per double bevel
Mechanised Bevel Burr Cleaning Time	Per bevel and per double bevel
Mechanised Bevel Re-Set-up Time	Per bevel and per double bevel (if bevel length exceeds rail length)
Marking Time	Per bevel and per double bevel
Part Connecting Time	Per part
Part Disconnecting Time	Per part
Part Moving Time With Crane	Per part
Crane Moving Time (empty)	Per part

Table 4.11 Occurrence of mechanised bevel time elements

Mechanised Bevelling Time			
Description	**Formula**	**Unit**	**Variable Declaration**
Cutting and burr cleaning time	$\sum_{i=1}^{N}\left[\left(0.223\cdot L_i+27+0.01\cdot L_i+18\right)\cdot Q_i\right]$	s	N : Number of bevels on part L_i : Length of bevel [mm] Q_i=2 if bevel is a double bevel else Q_i=1
Set-up and de-set-up time	$\sum_{i=1}^{N}92\cdot Q_i+\sum_{i=1}^{N}14\cdot Q_i+\sum_{i=1}^{N}round\left(\frac{L_i}{1270}\right)\cdot 63\cdot Q_i$	s	Rounding is to the lower integer
Handling time	$3.5\cdot D+114+196\cdot P$	s	D : Distance of storage from bevelling area [m] P=2 if part contains a double bevel else P=1
Marking time	$\sum_{i=1}^{N}\left(0.031\cdot L_i\cdot 2+16\cdot NL_i\right)\cdot Q_i$	s	$NL_i = 2$

Table 4.12 Mechanised beveling time estimation formulas

4.2.6. ***Manual Bevelling Time Estimation***

The time study showed that the total manual bevelling process time can be broken down into the following time elements:

1. Cutting and cleaning time.
2. Set-up and de-set-up time.
3. Re-set-up time.
4. Handling time.
5. Measuring and marking time.

These time elements can be calculated and summed together (according to the process flow diagram) to obtain the total estimated manual bevelling production time.

4.2.7. ***Constants for the Manual Bevelling Process***

The time study data was used to obtain constants for the above mentioned time elements.

Torch Set-up Time = 72 seconds

Definition:

Time taken by operator to ignite and tune flame, put on protective clothing and preheating material to it kindling temperature.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	60%
Cumulative error	-11%
Standard deviation the error	78%
Lower confidence limit of 90%	-30%
Upper confidence limit of 90%	30%
Reference	Appendix C.3.1 page C-IX

Table 4.13 Properties of torch set-up time element

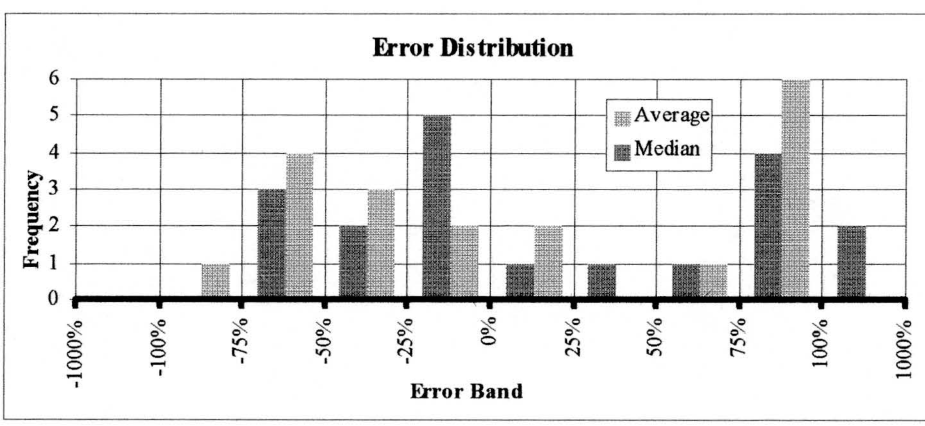

Figure 4.17 Error distribution for setup time estimation

The increase in frequency in error band 75% to 100% can be attributed to positioning of the torch for easy accessible places when torch set-up is very easy.

Torch De-Set-up Time = 10 seconds

Definition:

Total time taken by operator to turn flame down, put torch down and remove protective clothing.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	21%
Cumulative error	-10%
Standard deviation the error	26%
Lower confidence limit of 90%	-11%
Upper confidence limit of 90%	11%
Reference	Appendix C.3.1 page C-X

Table 4.14 Properties of torch de-set-up time element

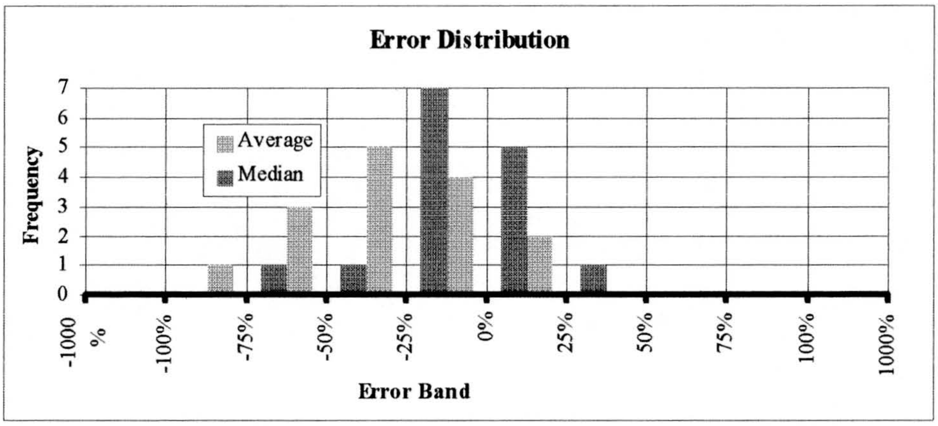

Figure 4.18 Error distribution for de-set-up time estimation

Manual Bevelling Time = 0.256·L+2 seconds

Definition:

Total time taken by operator for continuous cutting of bevel with length L.

Statistical method used to obtain constant	Robust data analysis
Valid range for formula	0≤D≤Operator Limit with L in [mm]
Average absolute error	8%
Cumulative error	-413%
Standard deviation the error	13%
Lower confidence limit of 90%	-5%
Upper confidence limit of 90%	5%
Reference	Appendix C.3.3 page C-XI

Table 4.15 Properties of manual bevel time element

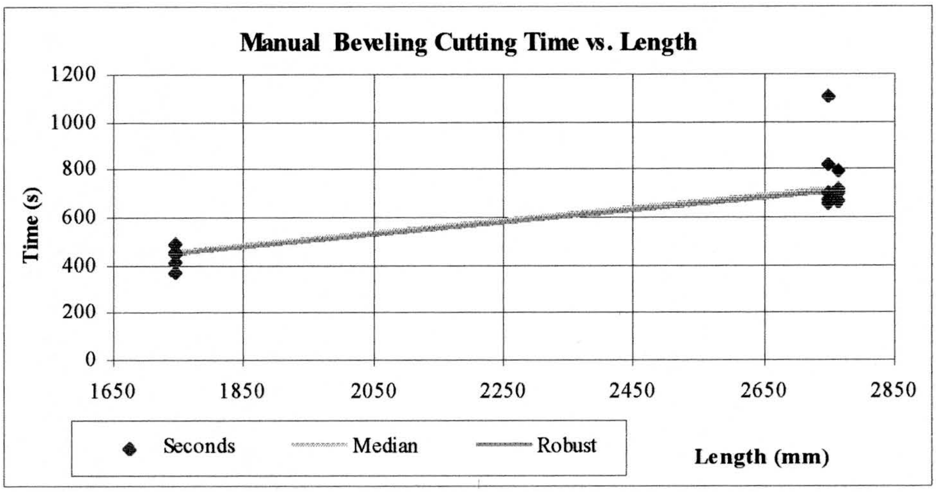

Figure 4.19 Manual bevelling cutting time vs. length

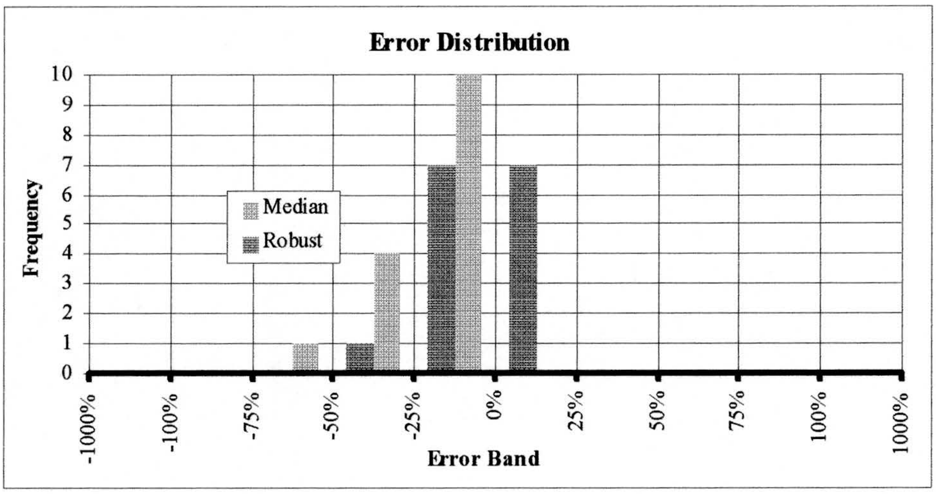

Figure 4.20 Error distribution for cutting time estimation

Manual Bevelling Cleaning Speed = 879 mm per minute

Definition:

The manual bevel cleaning time is defined as the bevel length divided by the cleaning speed. It is the time taken to remove cutting slag from the edge.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	30%
Cumulative error	-6%
Standard deviation the error	37%
Lower confidence limit of 90%	-23%
Upper confidence limit of 90%	23%
Reference	Appendix C.3.4 page C-XIII

Table 4.16 Properties of manual bevel cleaning time element

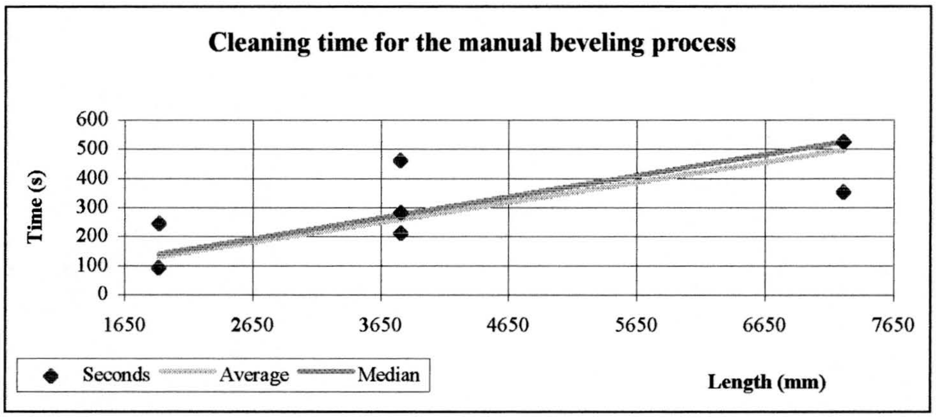

Figure 4.21 Manual bevel cleaning time vs. length

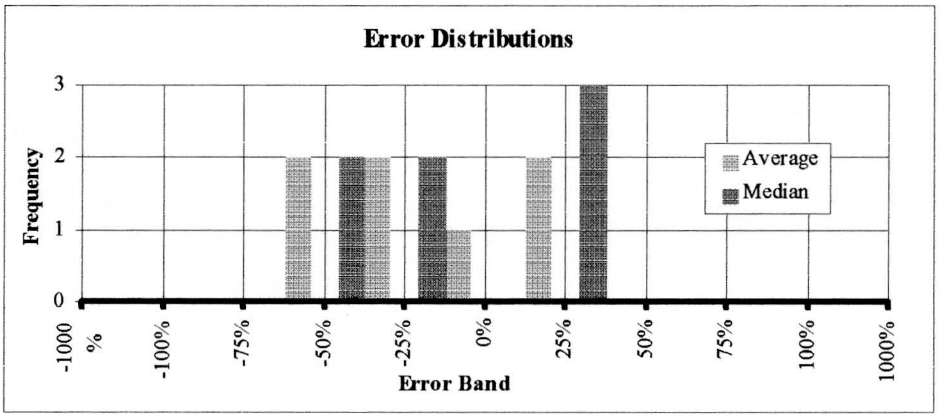

Figure 4.22 Error distribution for cleaning time estimation

The band spread gap (0%-25%) for the median bevelling speed can be attributed to the bevelling speed used by two different operators.

Manual Bevel Reposition Time = 21 sec

Definition:

Total time taken by operator to move a short distance without turning the flame down and re-heating the material to its kindling temperature when cutting a bevel section.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	44%
Cumulative error	-36%
Standard deviation the error	62%
Lower confidence limit of 90%	-9%
Upper confidence limit of 90%	9%
Reference	Appendix C.3.5 page C-XIII

Table 4.17 Properties of manual bevel repositioning time element

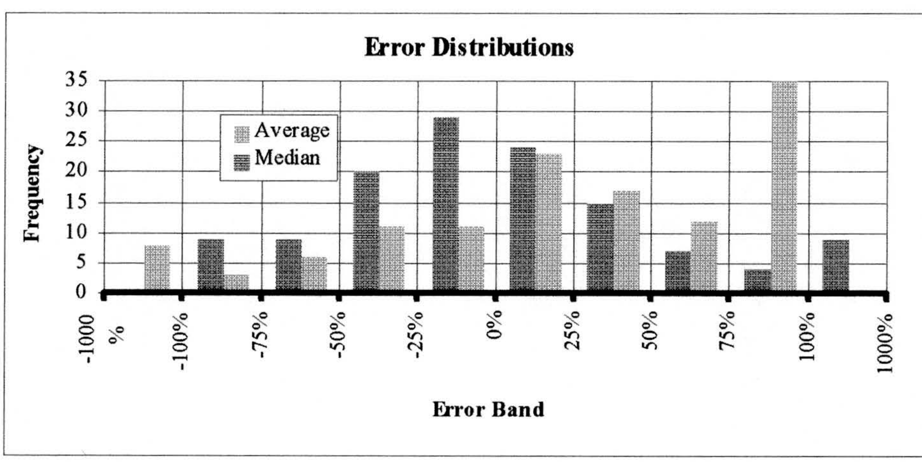

Figure 4.23 Error distribution for repositioning time estimation

Bevel Reposition without Torch Set-up Time = 32 sec

Definition:

Total time taken by operator to move a short distance without turning the flame down and re-heating the material to its kindling temperature when cutting a new bevel section.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	38%
Cumulative error	-7%
Standard deviation the error	74%
Lower confidence limit of 90%	-38%
Upper confidence limit of 90%	38%
Reference	Appendix C.3.6 page C-XVI

Table 4.18 Properties of repositioning without set-up time element

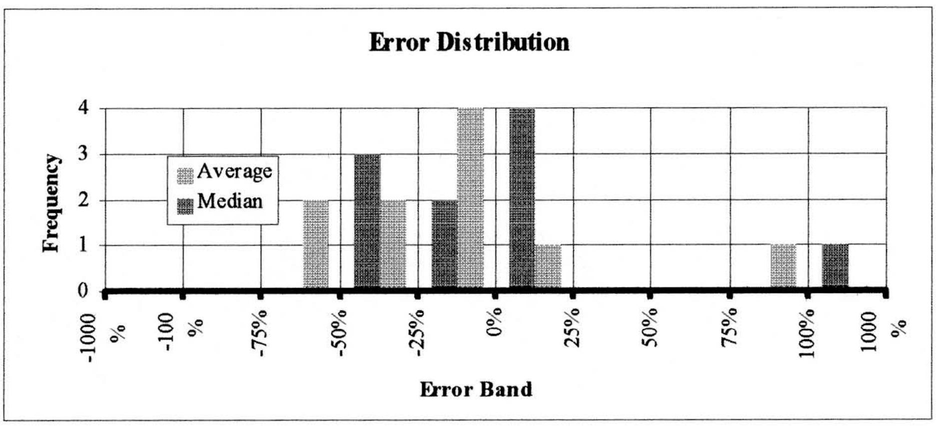

Figure 4.24 Error distribution for new bevel repositioning time estimation

Normal Reach for Manual Bevelling = 260 mm

Definition:

The average distance that an operator can cut without repositioning himself.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	65%
Cumulative error	-2%
Standard deviation the error	127%
Lower confidence limit of 90%	-18%
Upper confidence limit of 90%	18%
Reference	Appendix C.3.7 page C-XVII

Table 4.19 Properties of normal reach for bevelling constant

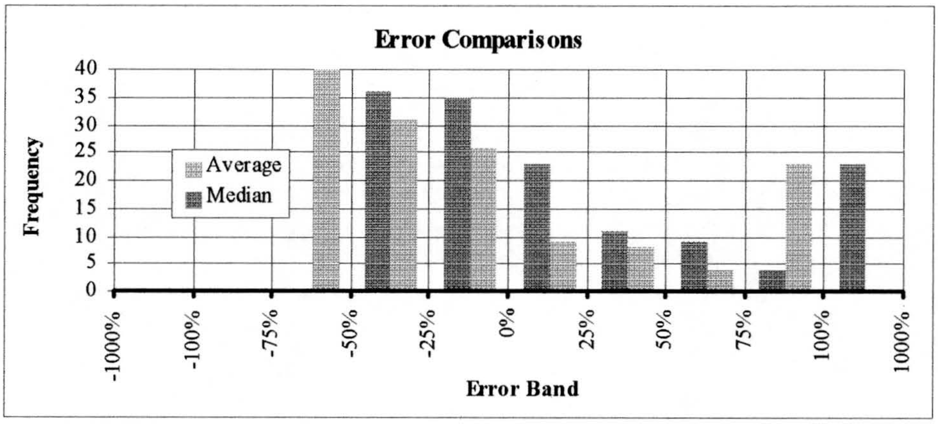

Figure 4.25 Error distribution for operator normal reach estimation

4.2.8. ***Time Estimation Procedure for the Manual Bevelling Process***

The time estimation model uses a combination (according to the process flow diagram) of the above mentioned constants and equations to obtain the total manual bevelling time estimation.

Table 4.21 summarises the manual bevelling time estimation formulas. These formulas estimates the bevelling time per part. The formulas were constructed according the process flow diagram, Figure 4.26. Table 4.11summarises the occurrence of the time elements.

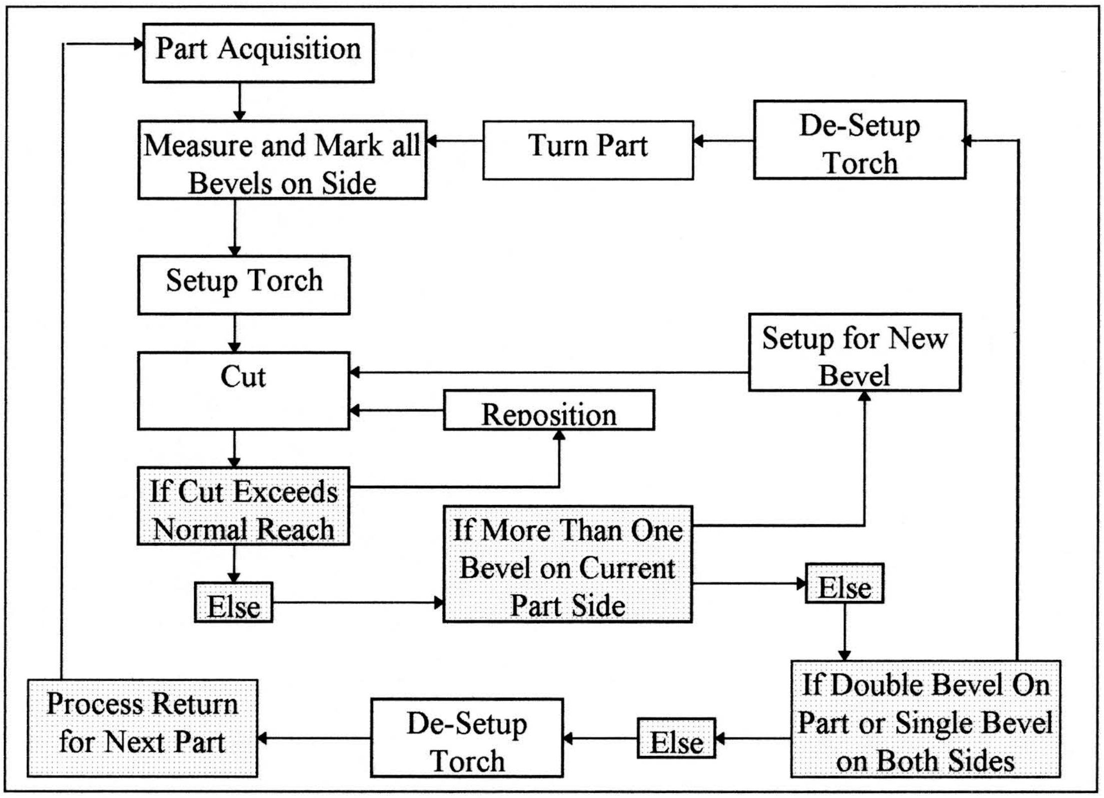

Figure 4.26 Process flow diagram for the manual bevelling process

Element Description	Occurrence
Torch Set-up Time	Per bevel and per bevel type
Torch De-Set-up Time	Per bevel and per bevel type
Manual Bevelling Time	Per bevel and per bevel type
Manual Bevel Cleaning Speed	Per bevel and per bevel type
Manual Bevel Reposition Time	Per bevel and double bevel if the bevel is longer than the normal reach of the operator
Bevel Reposition (no torch set-up)	Per single and per double bevel
Marking Time	Per bevel and per double bevel
Handling Time	Per Part

Table 4.20 Occurrence of manual bevelling time elements

Manual Bevelling Times			
Description	**Formula**	**Unit**	**Variable Declaration**
Cutting and burr cleaning time	$\sum_{i=1}^{N}\left[\left(0.256\cdot L_i+2+\frac{L_i}{879}\cdot 60\right)\cdot Q_i\right]$	s	L_i : length of bevel section [mm] N : Number of bevels on part Q_i=2 if bevel is a double bevel section else Q_i=1
Set-up and de-set-up time	$82\cdot P+\sum_{i=1}^{N}\left[round\left(\frac{L_i}{260}\right)\cdot 21\cdot Q_i\right]$	s	P=2 if part contains a double bevel else P=1 Rounding is to the nearest integer
Repositioning time for new bevel section	$(N_s+N_d\cdot 2-1)\cdot 32$	s	N_s : Number of single bevels on part N_d :Number of double bevels on part
Handling time	$3.5\cdot D+114+196\cdot P$	s	D : Distance of bevelling area from storage [m]
Marking time	$\sum_{i=1}^{N}(0.031\cdot L_i\cdot 2+16\cdot NL_i)\cdot Q_i$	s	NL_i : Number of lines to be marked (2)

Table 4.21 Manual beveling time estimation formulas

4.3. <u>Clean Grinding of Bevelled Edges Time Estimation</u>

4.3.1. <u>*Clean Grinding Overview*</u>

Clean grinding of prepared edges are necessary to remove any scale that may still be on the surface of the bevel. The cleaning of bevelled edges can be classified into two categories. Cleaning of manually bevelled edges and the cleaning of mechanised bevelled edges. The processes used for both of these edges are the same.

The cleaning speeds of a manually bevelled edge and a mechanised bevelled edge differs significantly. Cleaning of manually bevelled edges takes approximately ten times longer than the cleaning of mechanised bevelled edges. It is therefore important to include the cleaning times when doing a trade off between the two processes.

4.3.2. ***Model Construction***

Time study data was used to develop a model. The overall clean grinding time was broken down into smaller time elements that can be estimated more easily. These time elements are related to specific operator tasks and machine cycle times. Each element is then calculated and combined in a proper manner with the other time elements.

The handling for the clean grinding of bevelled edges is the same as the handling required for bevelling.

The time study data showed that the grinding disk usage is proportional to the grinding time. The data was recorded for an electric grinder with a power input of 2500W.

The time study showed that the total clean grinding time of bevelled edges can be broken down into the following time elements:

1. Grinding time.
2. Set-up and de-set-up time.
3. Handling time.
4. Disk change times.

These time elements can then be calculated and added together to obtain the total clean grinding time required.

4.3.3. ***Constants for Clean Grinding of Bevelled Edges***

The time study data was used to obtain constants for the above mentioned time elements.

The grinding set-up and de-set-up times are the same as those calculated for burr removal grinding.

Grind Time of Mechanised Bevelled Edges = $7.028 \cdot 10^{-4} \cdot A + 52$ seconds

Definition:

Total time taken by operator to clear the surface of the mechanised bevel sufficiently for the welding process.

Statistical method used to obtain formula	Least square fir method[3]
Valid range for formula	$9600 \leq A \leq 48000$ with A in [mm^2]
Average absolute error	41%
Cumulative error	-0%
Standard deviation the error	53%
Lower confidence limit of 90%	-27%
Upper confidence limit of 90%	27%
Reference	Appendix B.1.4.1 page B-V

Table 4.22 Properties of mechanised bevel grind time element

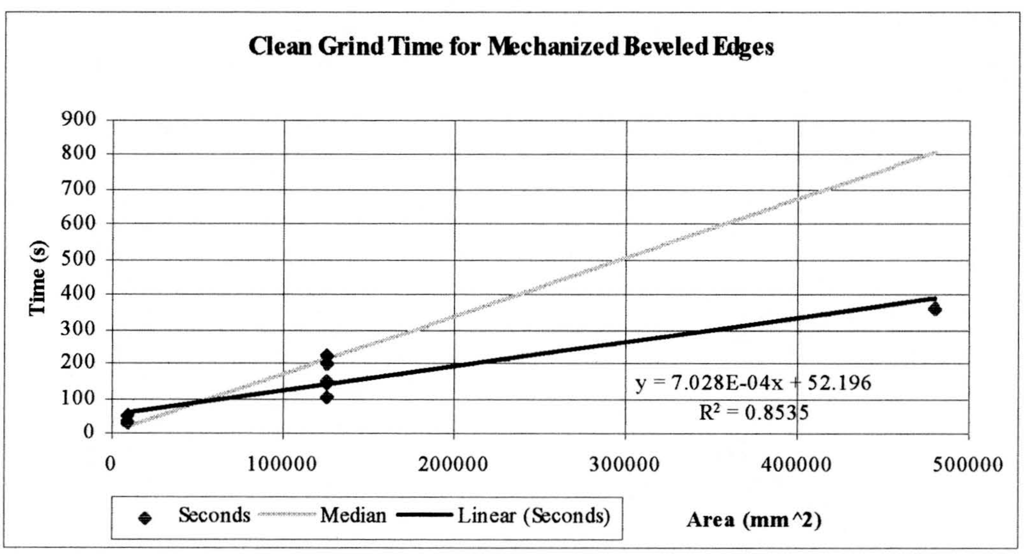

Figure 4.27 Grinding time for mechanised bevelled edges vs. area

[3] The recorded data could not be divided into three representative groups, therefore robust data analysis were not used.

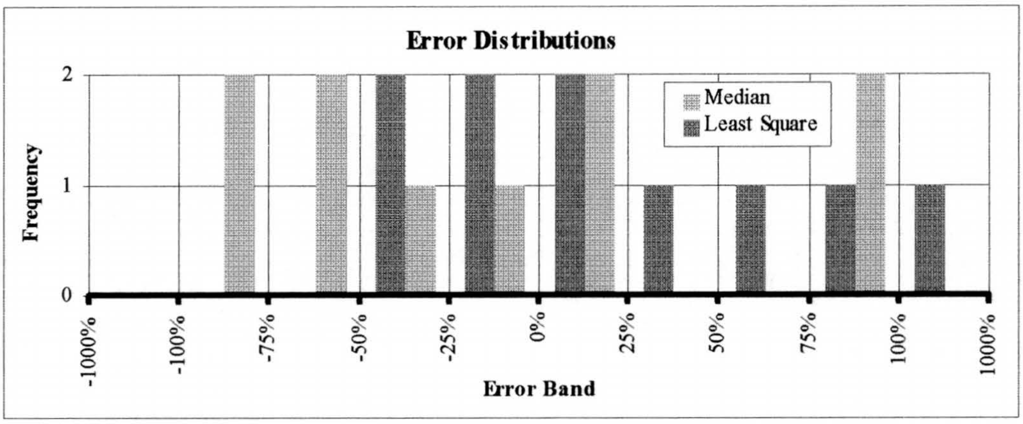

Figure 4.28 Error distribution for estimating the mechanised bevel grinding time

The poor error distribution can be attributed to blow holes on the surface of the plate which are caused by poor cutting torch flame settings, incorrect cutting speeds and clogged nozzles. These holes have to be removed with a grinder.

Grind Speed of Manually Bevelled Edges = 3487 mm^2 per min

Definition:

> Total time taken by operator to clear the surface of the manually bevelled edge sufficiently for the welding process. It is the surface area divided by the grinding speed.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	40%
Cumulative error	-20%
Standard deviation the error	47%
Lower confidence limit of 90%	-26%
Upper confidence limit of 90%	26%
Reference	Appendix B.1.4.2 page B-VI

Table 4.23 Properties for manual bevel grind time element

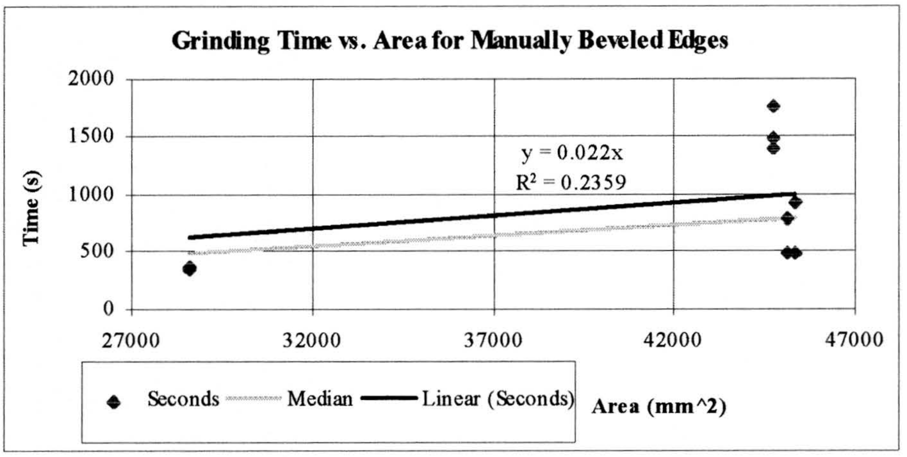

Figure 4.29 Grinding time vs. area

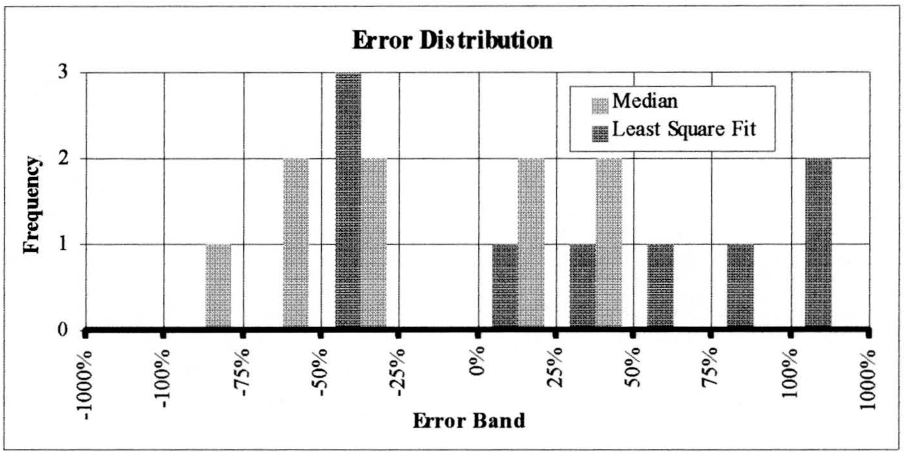

Figure 4.30 Error distribution for estimating manual bevel grinding time

Grind Time Per Disk =900 seconds

Definition:

The total time that the operator can grind with a standard grinding disk.

Statistical method used to obtain constant	Average of recorded data
Average absolute error	20%
Cumulative error	-0%
Standard deviation the error	23%
Lower confidence limit of 90%	-13%
Upper confidence limit of 90%	15%
Reference	Appendix B.1.4.3 page B-VII

Table 4.24 Properties of grind time per disk element

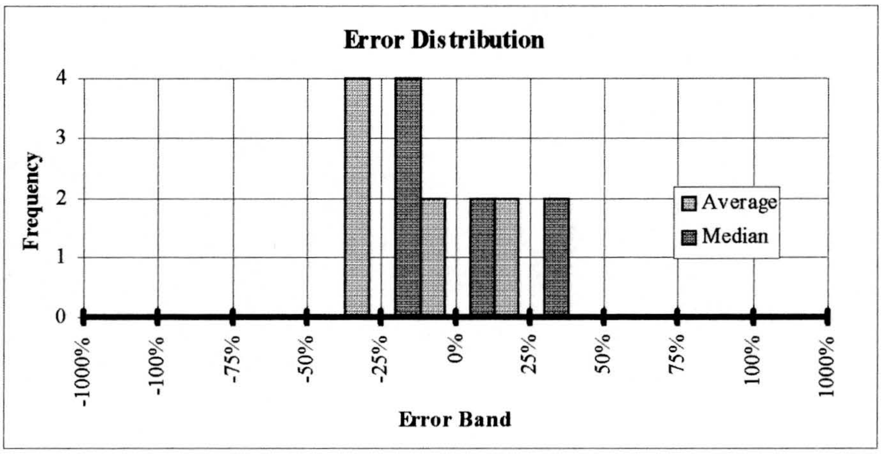

Figure 4.31 Error distribution for estimating the grinding time per disk

Disk Change Time = 107 seconds

Definition:

Total time taken by operator to collect new grinding disk, remove worn disk and fit new grinding disk.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	26%
Cumulative error	-8%
Standard deviation the error	33%
Lower confidence limit of 90%	-19%
Upper confidence limit of 90%	19%
Reference	Appendix B.1.4.4 page B-VIII

Table 4.25 Properties of disk change time element

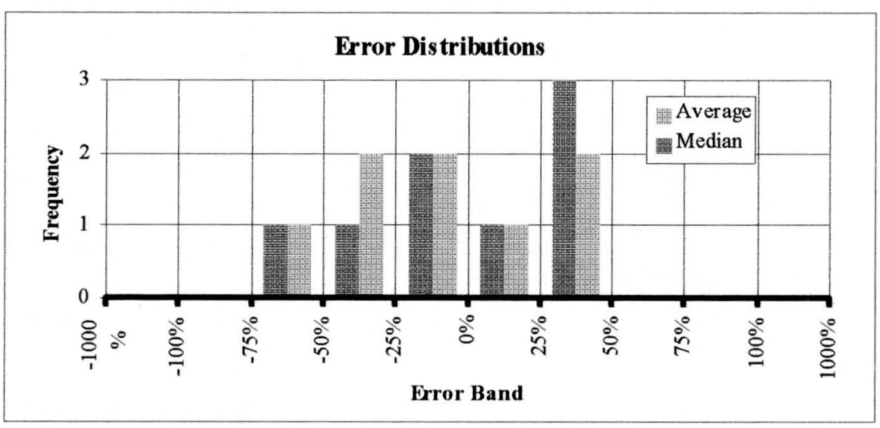

Figure 4.32 Error distribution for estimating disk change time

4.3.4. ***Grind Time Estimation Procedure for Bevelled Edges***

The time estimation model then uses a combination of the above mentioned constants to estimate the clean grinding time estimation of bevelled edges.

Table 4.27 summarises the bevelled edge clean grinding time estimation formulas per part. These formulas were constructed according to the process flow diagram, Figure 4.33. Table 4.26 summarises the occurrence of the time elements.

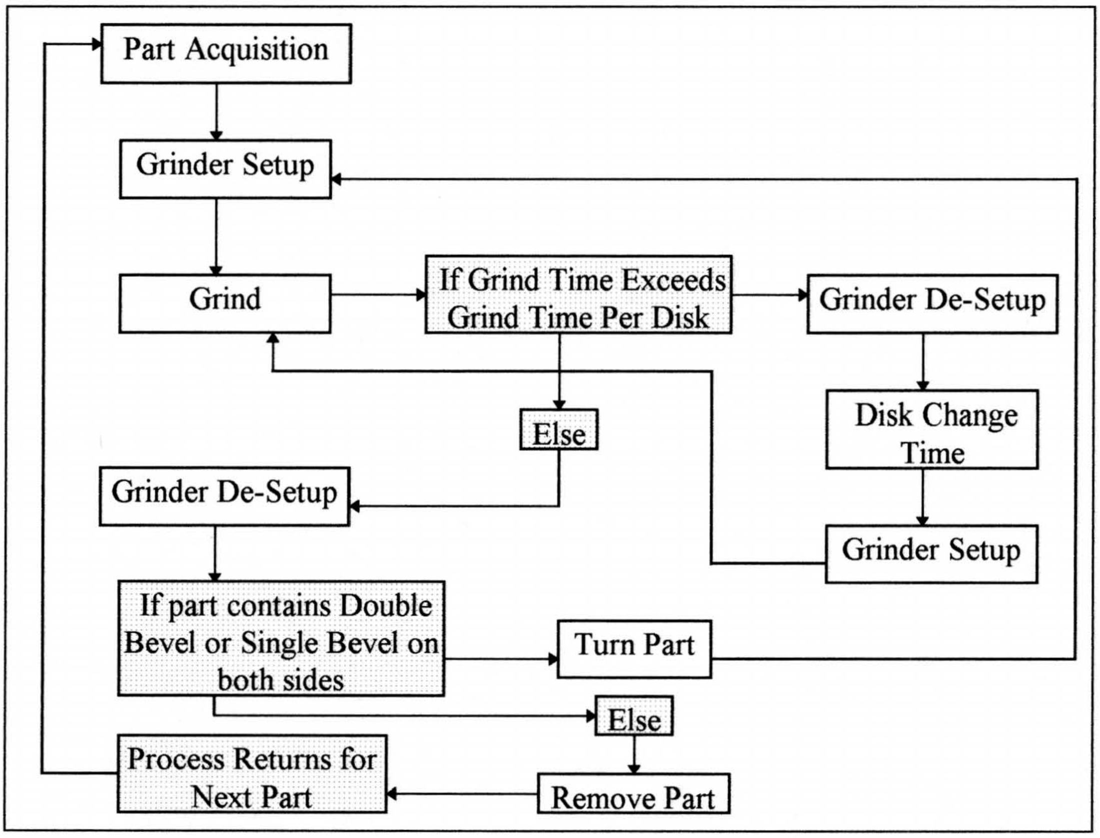

Figure 4.33 Process flow diagram for bevelled edge clean grinding

Element Description	Occurrence
Grind Time (mechanised bevelled edge)	Per mechanised bevelled edge
Grind Time (manual bevelled edge)	Per manually bevelled edge
Disk Change Time	Per number of disks required
Grind Set-up	Per bevel and per bevel type and per number of disks required
Grind De-Set-up	Per bevel and per bevel type and per number of disks required
Handling Time	Per part

Table 4.26 Occurrence of clean grinding time elements

Bevelling Sub Task Times			
Description	**Formula**	**Unit**	**Variable Declaration**
Grind time	$7.028 \cdot 10^{-4} \cdot A_1 + 52 + \frac{A_2}{3487} \cdot 60$	s	A_1 : Mechanised bevel area [mm^2] A_2 : Manual bevel area [mm^2]
Disks required	$round\left(\frac{T_{GrindingTime}}{900}\right)$		$T_{grindingTime}$: Total Grinding time on part [s] Rounding is to the higher integer
Set-up, de-set-up and disk change time	$159 \cdot Disks + 52 \cdot N_s + 104 \cdot N_d$	s	Disks = the number of grinding disks required
Handling time	$3.5 \cdot D + 114 + 196 \cdot P$	s	D : Distance of grinding area from storage. P=2 if part contains double bevel or single bevel on both sides, else P=1.

Table 4.27 Clean grinding of bevelled edge time estimation

5. Plate Bending Time Estimation

5.1. Overview of Plate Bending Process

Plate bending can be considered as an alternative manufacturing process for welding, when plates are to be joined at a relative angle [Feder, 1993]. When doing a trade off study between bending and other joining methods one has to consider the following:

- The availability of the manufacturing equipment, i.e. bending press and the bending press dies.
- The manufacturing limits of the bending press with respect to the length of bend that can be manufactured and the maximum force output of the press.
- Material elements such as yield stress, ductility and ultimate tensile stress.

It is known that the cycle time of a bending press is determined by the press force of the machine [Boothroyd et al. 1994]. The press force required is related to the material's mechanical properties, length of the bend and the material thickness. The model developed here focuses on the bending of plates with a bending press that has a maximum press force of 1200 ton. The bending time is further also related to the number of die changes and batch size.

5.2. Model Construction

The model focuses on three types of bends namely :

1. A normal bend.
2. A channel type bend.
3. A curved bend.

A normal bend is any type of bend that can be made without interference of the upper or lower die. Interference normally occurs when the part contains a deep narrow channel section.

A channel type bend is any two bends that forms a channel type section. This channel type section may require back set in order to avoid interference of the upper die with the part. At the factory where data was recorded the operator decides when back set is required. This is done by preparing a test sample and bending it to determine if back set is required or not. The depth of back set required is also determined during this operation.

A curved bend is any bend with a large radius which cannot be bent with a normal die. These bends are produced by a series of smaller bends close to each other and are approximately 2-4 cm apart. This distance is known as the inching distance and the method, the inching method. Complex bend types can be bent with this method including square to round sections. A study of bent plates showed that the inching distance varies from one operator to another.

The total time required for bending is broken down into smaller time elements. This was done for the three types of bends specified above. These time elements are then determined from the time study data. Each element is then determined and combined in a proper manner with the other elements (as depicted in the process flow diagrams).

Another process for bending curved bends is plate rolling. This process gives a smoother bend radius, especially for plate thicknesses in the range 15-40mm.

5.3. <u>Time Estimation</u>

The time study showed that the total bending time can be broken down into the following time elements:

1. Bending press set-up (changing the upper and lower dies of the bending press).
2. Material acquisition (getting material from within a radius of 10 meters).
3. Material preparation (elementary marking and part orientation).

4. Bending (the actual time that the press takes to complete one bend. For curved bending it is defined in the form of a bending speed).
5. Part removal (moving a part from the press to an area within a radius of 10 meters from the machine).
6. Back set bending for deep narrow channel sections.

These time elements are summed together (according to the process flow diagram) to obtain the total bending time.

5.3.1. ***Constants for Plate Bending***

The time study data was used to obtain constants for the above mentioned time elements.

Machine Set-up Time = 1465 seconds

Definition:

Total time taken by operator to change upper and lower die of the bending press.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	9%
Cumulative error	-0%
Standard deviation the error	10%
Lower confidence limit of 90%	-7%
Upper confidence limit of 90%	9%
Reference	Appendix D.1.1 page D-II

Table 5.1 Properties of machine set-up time element

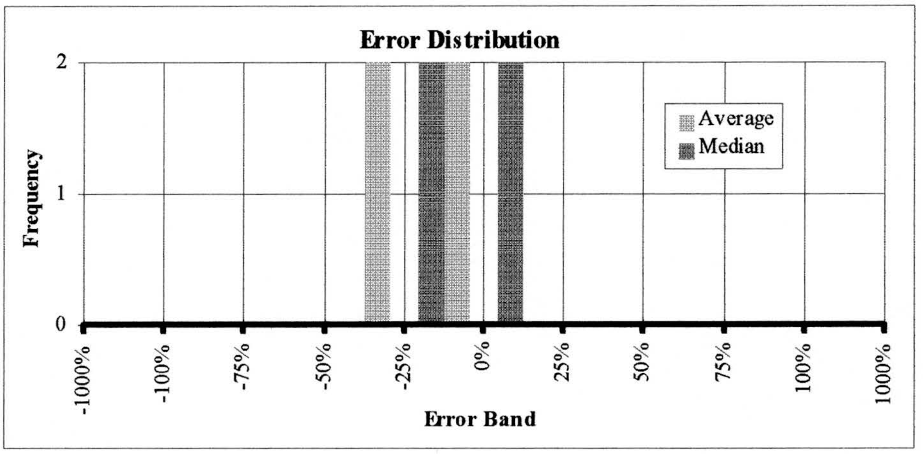

Figure 5.1 Error distribution for machine setup time estimation

Material Acquisition Time = 99 seconds

Definition:

Total time taken by operator to retrieve plate material with overhead crane from nearby location (maximum 5 meters).

Statistical method used to obtain constant	Median of recorded data
Average absolute error	58%
Cumulative error	2%
Standard deviation the error	69%
Lower confidence limit of 90%	-24%
Upper confidence limit of 90%	24%
Reference	Appendix D.1.2 page D-III

Table 5.2 Properties of material acquisition time element

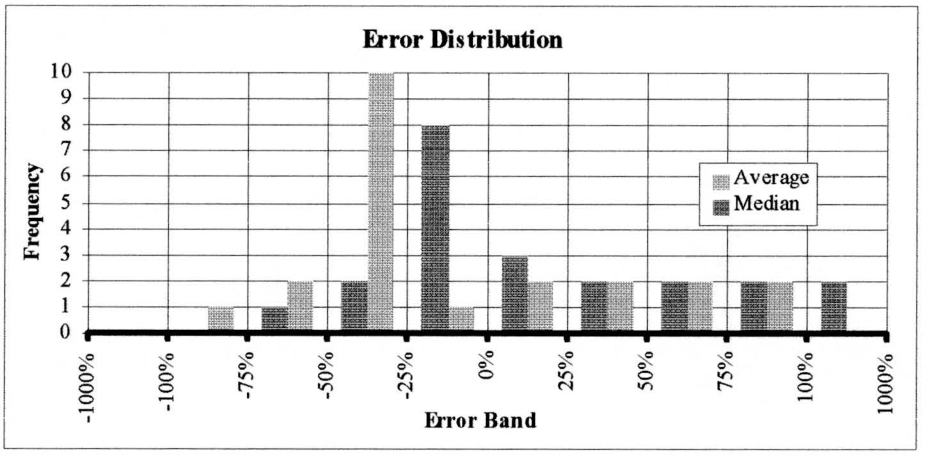

Figure 5.2 Error distribution for material acquisition time estimation

Normal Bend Cycle Time = 123 seconds

Definition:

Total time taken by bending press to bend one bend with a certain die set-up (bend is compared to a template, hence accuracy is high).

Statistical method used to obtain constant	Median of recorded data
Average absolute error	40%
Cumulative error	-16%
Standard deviation the error	51%
Lower confidence limit of 90%	-18%
Upper confidence limit of 90%	18%
Reference	Appendix D.1.3 page D-IV

Table 5.3 Properties of normal bend cycle time element

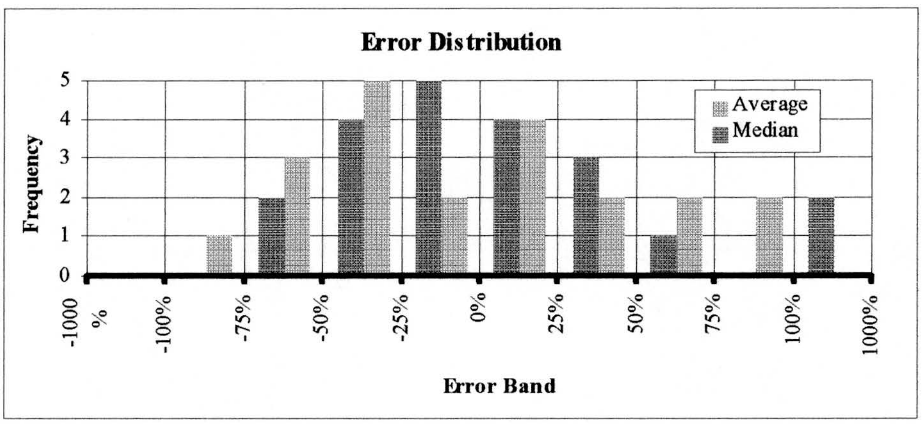

Figure 5.3 Error distribution for bend cycle time estimation

Part Preparation Time = 509 seconds

Definition:

Total time taken by operator to fine tune machine for a specific bend on a part (e.g. set stoppers at back).

Statistical method used to obtain constant	Average of recorded data
Average absolute error	18%
Cumulative error	0%
Standard deviation the error	22%
Lower confidence limit of 90%	-14%
Upper confidence limit of 90%	14%
Reference	Appendix D.1.4 page D-V

Table 5.4 Properties of part preparation time element

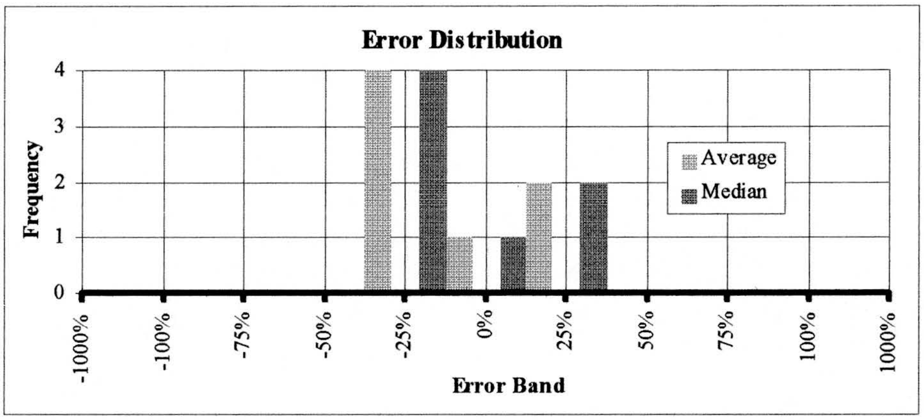

Figure 5.4 Error distribution for part preparation time estimation

Cycle Time for Back Set Bend = 27 seconds.

Definition:

Total time taken by machine to make a back-set bend type for channel sections (accuracy not required).

Statistical method used to obtain constant	Median of recorded data
Average absolute error	19%
Cumulative error	-17%
Standard deviation the error	28%
Lower confidence limit of 90%	-18%
Upper confidence limit of 90%	18%
Reference	Appendix D.1.5 page D-VI

Table 5.5 Properties of back set bend time element

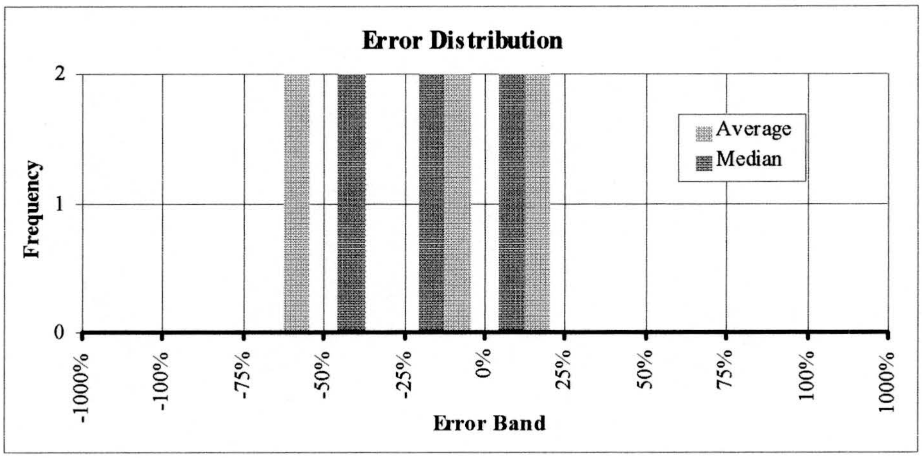

Figure 5.5 Error distribution of back set bending time estimation

Part Removal Time = 53 seconds

Definition:

Total time taken by operator to remove part from machine to nearby location (maximum 5 meters) on floor with the aid of an overhead crane.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	29%
Cumulative error	-7%
Standard deviation the error	34%
Lower confidence limit of 90%	-12%
Upper confidence limit of 90%	12%
Reference	Appendix D.1.6 page D-VII

Table 5.6 Properties of part removal time element

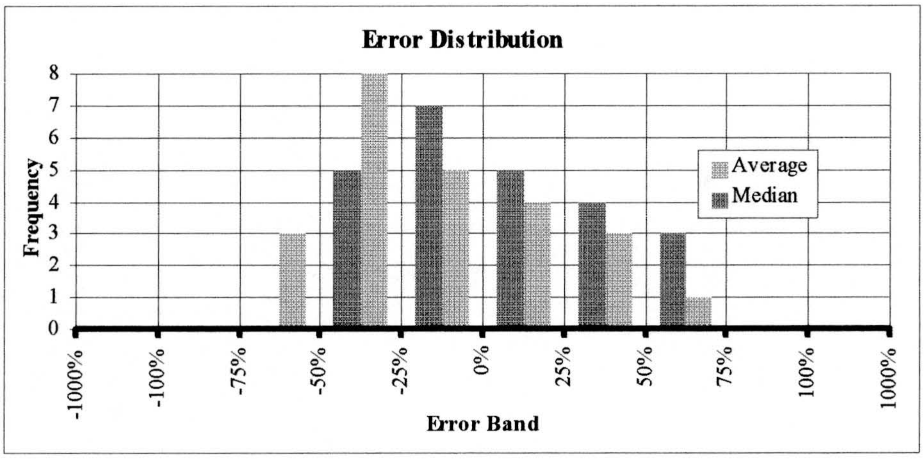

Figure 5.6 Error distribution of part removal time estimation

Inching Speed =31.37 mm per minute

Definition:

The inching time is defined as the total length of a curved section in a part divided by inching speed. This is the total time taken to make a series of small bends in order to produce a part with a large radius bend.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	12%
Cumulative error	-7%
Standard deviation the error	18%
Lower confidence limit of 90%	-12%
Upper confidence limit of 90%	12%
Reference	Appendix D.1.7 page D-IX

Table 5.7 Properties of inching bend time estimation

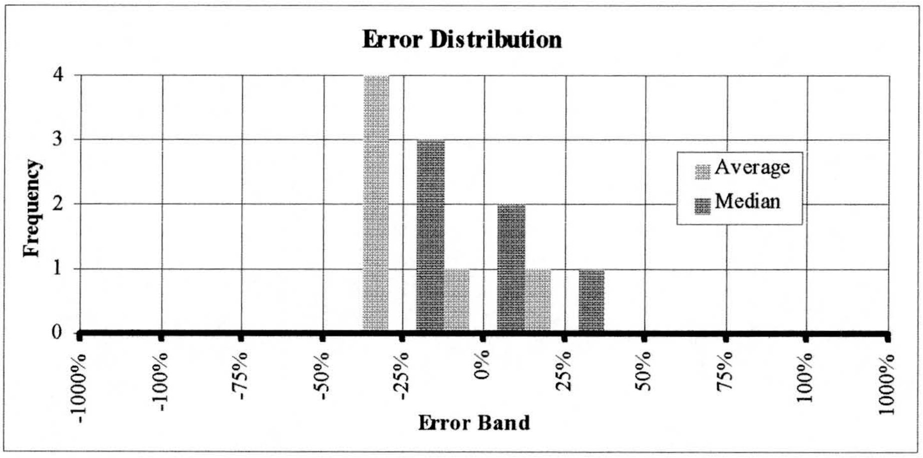

Figure 5.7 Error distribution of curved bending time estimation.

5.3.2. *Time Estimation Procedure for Plate Bending*

The time estimation model uses a combination of the above mentioned constants to obtain the total bending time estimation.

The time estimation formulas presented in Table 5.9 estimates the bending time per batch of parts. The time per part can also be obtained by setting N=1. These formulas were constructed according to the process flow diagrams, Figure 5.8, Figure 5.9, Figure 5.10. Table 5.8 summarises the occurrence of bending time elements.

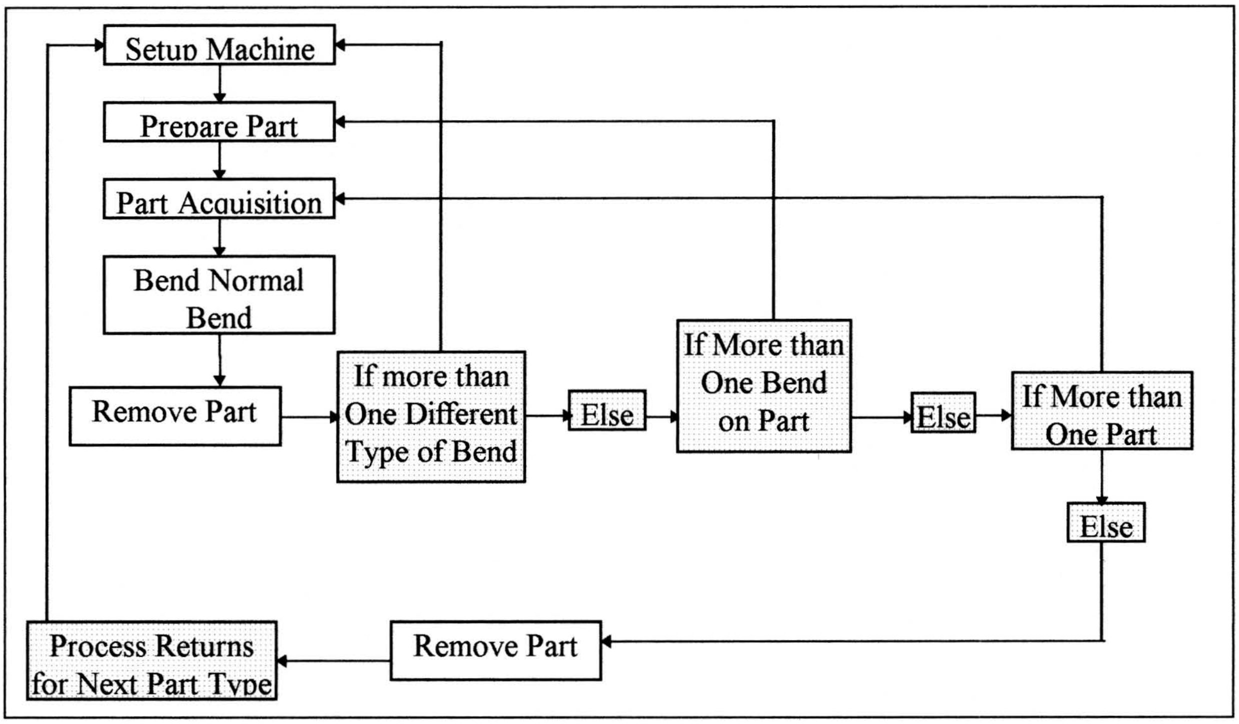

Figure 5.8 Process flow diagram for normal type bends

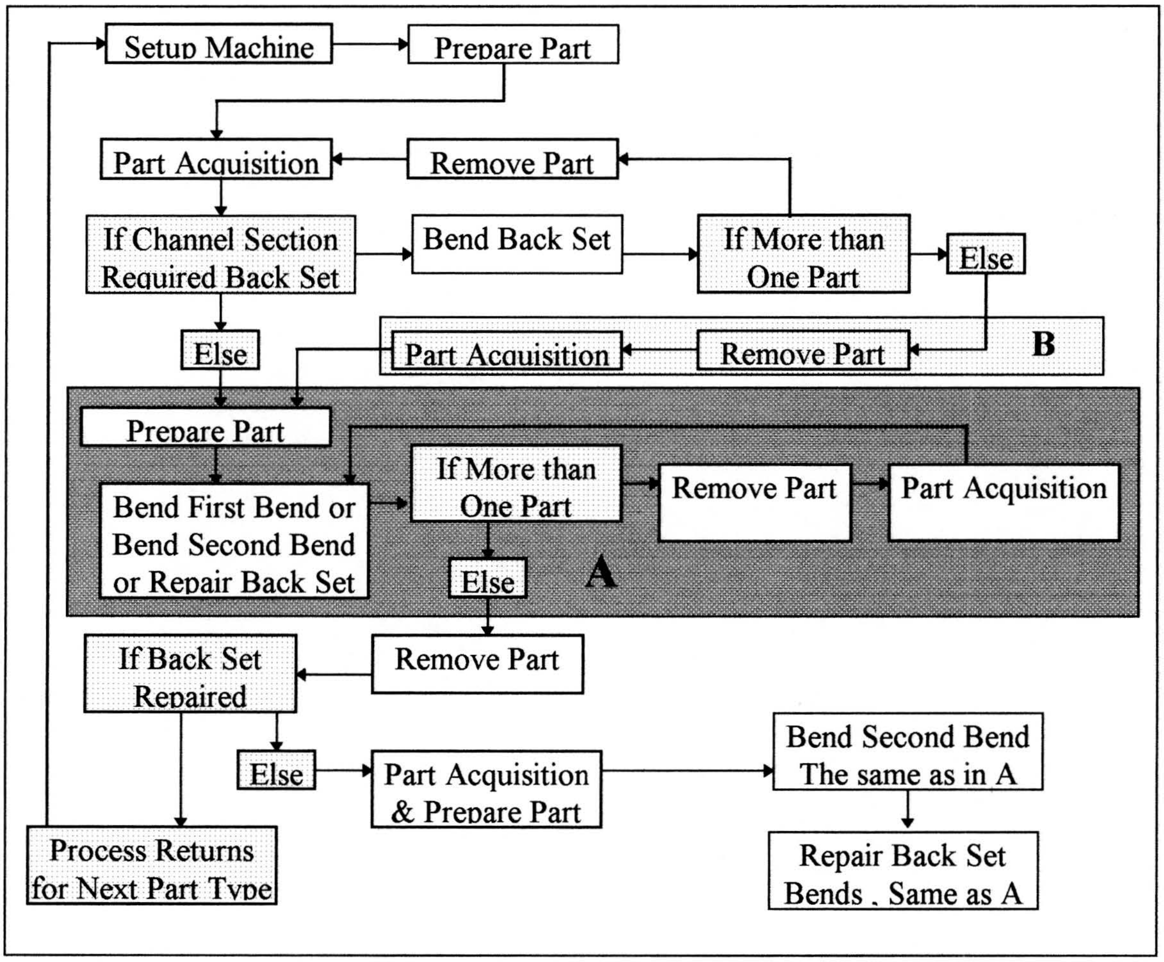

Figure 5.9 Process flow diagram for channel type bends

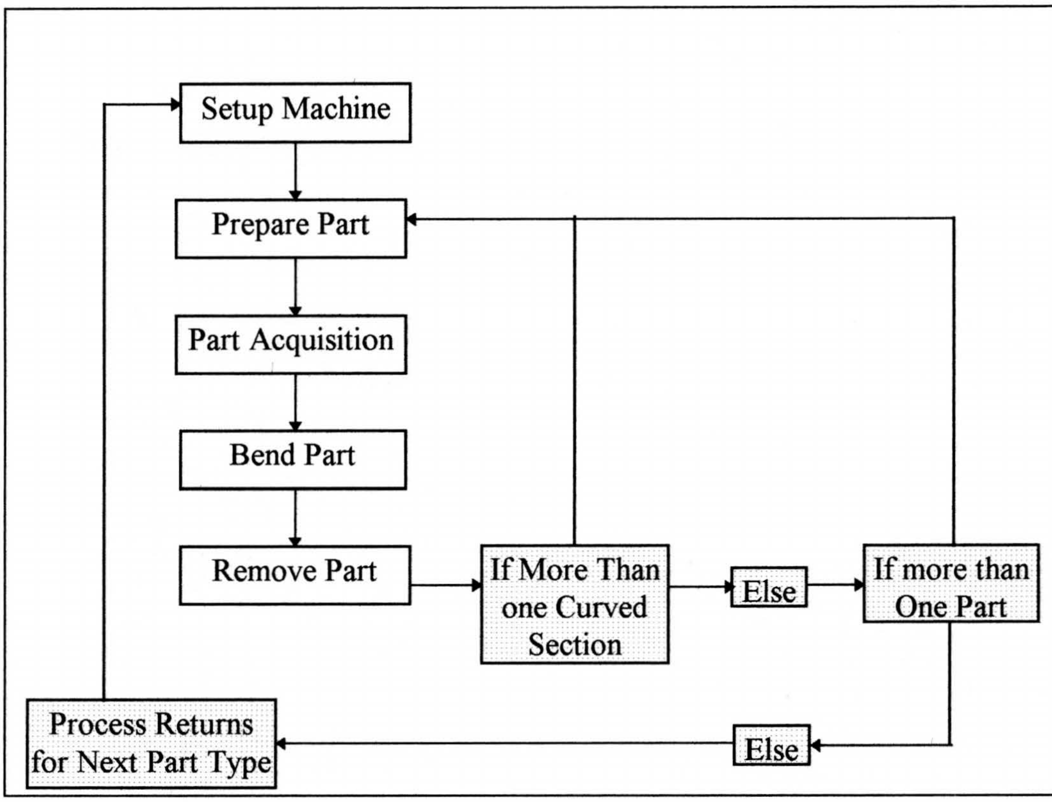

Figure 5.10 Process flow diagram for curved type bends

Element Description	Occurrence
Machine Set-up Time	Per batch and per number of different bends in part(s) that require additional die set-ups
Material Acquisition Time	Per part and per bend
Normal Bend Cycle time	Per bend
Part Preparation Time	Per bend in part
Back-set Bend Cycle Time	Per channel type bend that require back-set bend
Part Removal Time	Per part and per number of bends in part
Curved Bend Time	Per curved type bend(s) in part

Table 5.8 Occurrence of bending time elements

Plate Bending Time			
Description	**Formula**	**Unit**	**Variable Declaration**
Normal bend time[4]	$N \cdot S \cdot 275 + 1465 \cdot Q + 509 \cdot S$	s	N : Number of same parts S : Number of normal bends in part Q : Number of different types of normal bends
Channel bend time[4]	$1465 \cdot C + 1018 + 550 \cdot N + B_s \cdot (1018 + 454 \cdot N)$	s	C : Number of Setups required for Channel section B_s=1 if back set is required else B_s=0
"Back Set" Condition	$W_c - D_c > \frac{U_{dw} \cdot \sqrt{2}}{2}$		W_c : Width of channel [mm] D_c : Depth of Channel [mm] U_{dw} : Upper die width [mm]
Curve bend time[4]	$1465 + \sum_{i=1}^{B} N \cdot \left(661 + \frac{L_i}{31.37} \cdot 60\right)$	s	B : Number of curved sections on part L_i : Length of curved section [mm]

Table 5.9 Bending time estimation formulas

The number of different types of normal bends (Q) in the part is determined by counting every bend that requires a different die in the bending press. The number of normal bends is the sum of all bends contained in the part excluding any possible bends required to produce a channel or curved type bend.

The number of set-ups required for a channel section will be more than one if the channel section is not symmetric. This generally occurs if the corner radiuses of the channel section is not the same. The condition for back set is only valid for channel type sections that have 90° corners on both sides.

[4] This formula estimates the time for two operators performing the bending tasks

6. Tack Welding Production Time Estimation

6.1. Overview of Assembling

There are many sound reasons for focusing on a product's assembly attributes at the design stage. By its very nature, consideration of the assembly tasks focuses the designer's attention on the whole product, all its component parts and their inter-relationship [Miles, 1989]. When the designer is aware of the assembly attributes of products and the tasks required to assemble a product, he will tend to design products with a lower part count and product parts with easier assembly features [Helander, 1994]. Good assembly attributes will reduce product costs and, should the opportunity arise, permits the implementation of cost effective assembly automation [Miles, 1989; Helander, 1994]. Assembly characteristics of a product should be established at an early stage of the design process when the opportunity for change is greatest [Miles,1989; Boothroyd, 1994; Helander, 1994; Hundal,1995].

The evaluation of assembly attributes on a qualitative basis will identify weaknesses with respect to assembly time, of a specific design, and it will facilitate design improvements. There are currently at least three systems available to evaluate the assemblability of a product. They are [Miles; 1989]:

1. The Hitachi Assembly Evaluation Method. The AEM method does not distinguish between manual, robot and dedicated automatic assembly. Two reasons are put forward for this : the strong correlation between the degree of assembly difficulty by manual, robotic and dedicated assembly, and the difficulty in predicting the production mode at the design stage.
2. The Boothroyd and Dewhurst Method. This method draws a sharp destinction between manual, robotic and dedicated assembly and there are separate analysis systems for each of these areas. The Boothroyd and Dewhurst method suggests that the best way to achieve assembly cost reduction is to reduce the number of components first and then to ensure that the individual components have easy assemblability.

3. The Lucas Design for Assembly Procedure. The aim of this procedure is to apply it at an early design stage. It shares with the Boothroyd and Dewhurst procedure, the desire to reduce part count and ensure easy part assemblability. The Lucas procedure however focuses more on the reduction of part count than the other procedures because of the snowball effect that part count has on overall production cost.

Design for Assembly (DFA) should be considered at all stages of the design process. Design engineers, therefore, need a design tool that will give them an indication of the ease of assembly of the product at the design stage. The design tool must be easy to use and provide quick results. It should ensure consistency and completeness in its evaluation, eliminate subjective judgement from design assessment, allow free association of ideas and identify assembly problem areas [Boothroyd,1994].

The process time of manual assembly can be broken down mainly into two time elements [Boothroyed et. al. 1994] :

1. Handling
2. Insertion and fastening.

Designers can follow general design rules to improve the ease of part handling and insertion.

The general guidelines for part handling [Boothroyd,1994], (with the authors extension to guidelines for heavy engineering products) are :

1. Design parts with the maximum possible symmetry. The designer can specify the bevelling properties of a plate so that left hand and right hand components of a product can be interchangeable. This will reduce the number of different parts required and improve the assembler's knowledge of the product and assembly features. It will also avoid accidental confusion between left hand and right hand parts.
2. Parts that cannot be designed for symmetry must be designed to be obviously asymmetric.

3. Provide features that will prevent the jamming of parts that tend to nest or stack when stored in bulk.
4. Avoid features that will allow tangling of parts to take place when stored in bulk.
5. Avoid parts that are delicate, flexible, very large or hazardous to handle. The designer must, if possible, avoid the use of long thin plates since these parts will have to be supported when they are being moved.

The general guidelines for insertion and fastening can then also be extended to guidelines for heavy engineering products :

1. Design so that there is little or no resistance to insertion. The designer should not specify too close tolerances, especially in thicker plate sections. Trimming of parts almost always requires additional handling time along with the trimming time.
2. Standardise by using common parts, processes and methods across all models or even product lines to permit the use of higher volume processes that normally result in lower product cost.
3. Avoid, where possible, the need to hold parts down to maintain their orientation during manipulation of the assembly or during the placement of another part. The designer should avoid the occurrence of joining more than two parts or assemblies at once. This requires extensive checking and rechecking before the parts can be fastened. The use of jigs will also partly eliminate such problems.
4. Use pyramid assembly - fit smaller parts on to larger parts. This will reduce the risk of the whole assembly shifting when a smaller part is being fixed to it.
5. Avoid the need to reposition the partly finished assembly so that other parts can be fitted.

The cost estimation procedures currently in use mainly focus on the assembly of smaller products and not heavy fabricated assemblies. It was therefore found necessary to formulate a DFA tool for large and heavy fabricated assemblies, based on the same principles and which can be incorporated into the same general DFA procedure.

The model developed in this thesis considers part acquisition as handling time, and tack welding as insertion. Fastening is considered as welding and will be discussed in the following chapter. The model will, therefore, be referred to as the tack welding model.

6.2. Tack Welding Model Construction

The total time required for tack welding is broken down into smaller time elements. These time elements are related to specific operator tasks. Each element is calculated and combined in a proper manner with the other elements (as depicted in the process flow diagrams).

The assembly of fabricated heavy engineering assemblies uses larger and heavier parts than most other assemblies. Most of the parts are fabricated from plate material. The assemblies are manufactured by aligning plate edges and tack weld them together so that they can be welded at a later stage. The basic procedure followed by the operator (boiler maker) is:

1. Acquire part.
2. Position part.
3. Tack weld the joining edges.

The handling time of large and heavy parts are much longer than that of small components, mainly because the assembler has to make use of an overhead crane. The time study data showed no correlation between part weight and acquisition times. The handling time was, however, greatly influenced by the acquisition distance.

The time study data showed that the positioning and tacking time of a part were related to the component's:

- Mass.

- Length of the joining line that has to be tack welded.
- Number of joining lines that the part makes with the rest of the assembly.
- Plate thickness.
- Part curvature.

The joining line of a part is defined as the total length that has to be tack welded, if the plate is thick and it has to be tack welded on both sides then the joining line is double that of the edge length. The number of joining lines is defined as the number of separate edges of a part that is in contact with the rest of the assembly. The thickness of a part is defined as the plate material thickness, or the average thickness of the part for parts or sub assemblies which do not have an uniform thickness.

Additional trimming time is often required when the assembler attempts to fit a part but finds that the part has not been pre-manufactured correctly. Such parts need to be removed and trimmed until they fit properly. The additional time required for part correction can constitute to a considerable portion of the total tack welding time, especially when a part needs to be trimmed more than once.

The data showed that the additional time required to assemble a part due to fit-up problems ranged from 23% to 186% of the assembly time with no fit-up problems. The data showed that 20% of all parts required trimming, 71% of parts with a curve required trimming and 6% of parts without a curve required trimming. The trimming time for curved parts had an average of 88% additional trimming time. The trimming of flat parts had an average of 78% additional trimming time. This amounted to an additional 22% in tack welding time for all the recorded data.

6.3. <u>Time Estimation</u>

The time study have broken the total assembling time down into the following two elements : part acquisition time, and positioning and tacking time of the part.

The model was constructed for the tacking time alone (trimming times were deducted from the total tack welding time), because trimming is not required for each part.

The formulas presented in Table 6.2 and Table 6.6 were constructed from the following process flow diagram.

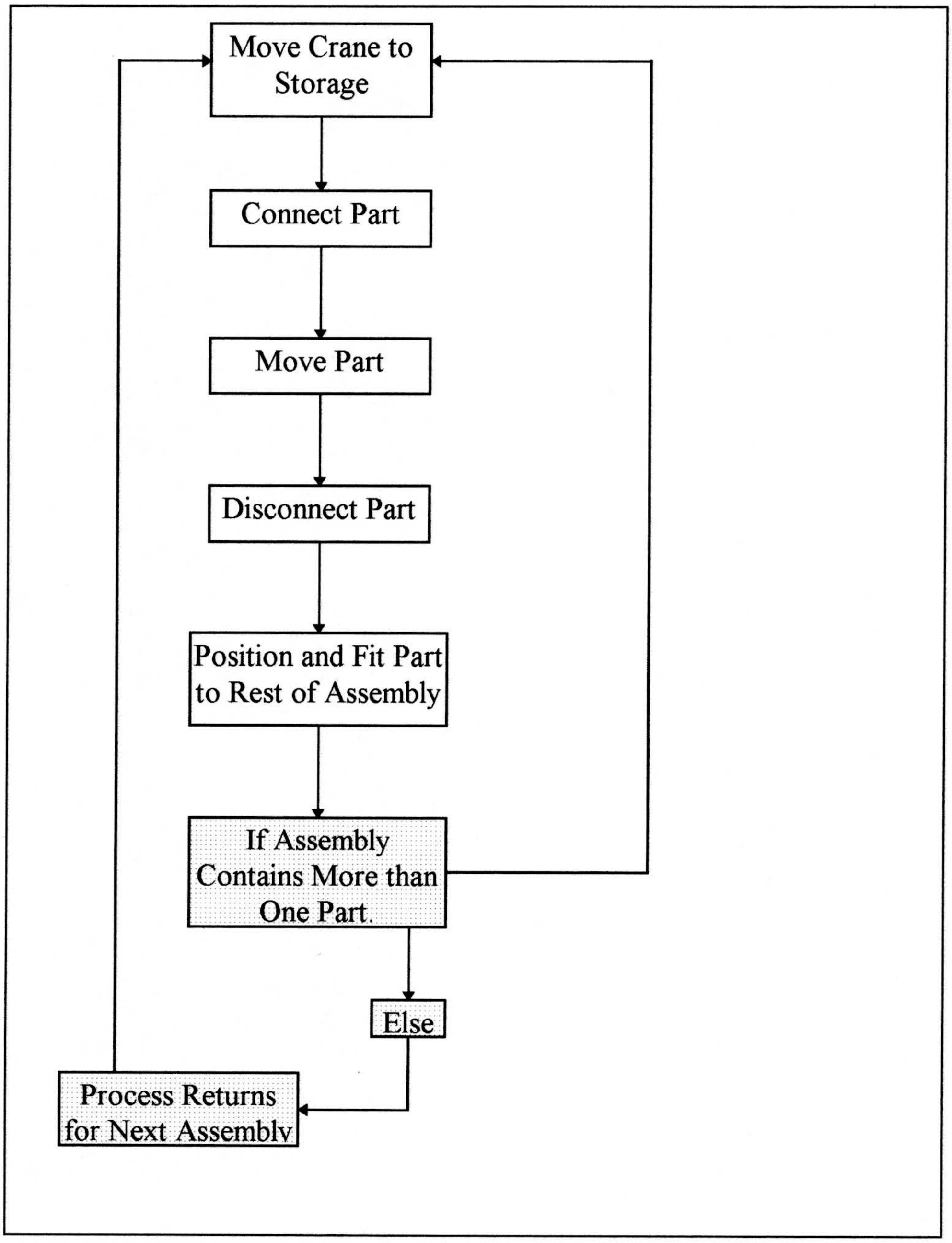

Figure 6.1 Process flow diagram for handling and tack welding

The model then assumes a correction factor for trimming that can be expected for the assembly.

6.4. Handling Time Estimation

The procedure for calculating the handling time of components, to and from the storage bay, is similar to the one depicted for weld joint preparation (bevelling). The handling time, depicted with this formula, is for part acquisition only and does not include crane acquisition time (as depicted in the process flow diagram). This is because the operator is constantly busy with the crane during the assembling process. The constants used in this formula are the same as those used for weld joint preparation handling time estimation.

The time formula presented in Table 6.2 estimates the acquisition time per part. The time elements used for the construction of the formula are the same as those presented in **Constants for Handling Time** on page 45. Table 6.1 summarises the occurrence of the relevant handling time estimation elements for tack welding.

Element Description	**Occurrence**
Part Connecting time	Per part
Part disconnecting Time	Per part
Part Moving Time With Crane	Per part
Crane Moving Time (empty)	Per part

Table 6.1 Occurrence of handling time elements

Material Acquisition Time			
Description	**Formula**	**Unit**	**Variable Declaration**
Handling Time	$3.5 \cdot D + 114$	s	D : Distance of assembly area from storage [m]

Table 6.2 Tack welding material acquisition time estimation formula

The data was recorded for parts which were laid down on the shop floor ±4 meters from the assembly location. Parts that were light enough to be carried by hand were not included in this comparison (parts that weighed less than 20 kg). There were only two such parts and their acquisition times were far less than the rest of the recorded times. The handling model gave an average absolute error of 64% and a cumulative error of -19% for the recorded acquisition times. The standard deviation of the error was 66%. Statistical analysis showed, with a confidence of 90%, that the error was less than 0%±16% for estimating the recorded times.

6.5. **Basic Tack Welding Time Estimation**

The basic tack welding formula was constructed by first making use of a multiple linear regression for the assembly times (excluding trimming). This was done with the following as variables :component weight, length of joining line, number of joining lines, plate curvature and plate thickness as variables (all variables recorded).

The following analysis was done to determine a time estimation equation:

1. Median times were determined for all similar data points. This reduced the data point count used for the formula construction from 66 to 44 data points.
2. A multiple linear regression (MLR) was performed on the new data set with: Part weight (W) [kg], Joining length (L) [mm], Number of joining lines (NL) [], Part curvature (C) [] and Material thickness (T) [mm] as variables. The average absolute error was then determined for the initial data set (66 point data set). The average absolute error for estimating the tack welding time with the formula derived here was 31.2% (see Table 6.3). The correlation coefficient was 0.709.
3. Each variable was then excluded separately from the MLR and a new MLR analysis was performed on the remaining data (44 point data set). This was done to determine the variables with the most and least influence on the tack welding time estimation. The average absolute error was then determined for the initial data set (66 point data set). Table 6.3 summarises the errors obtained.
4. The MLR analysis which produced the greatest error decrease, relative to the MLR with all variables, indicate that the variable has no or very little influence on the tack welding time. This showed that the number of

joining lines (NL) had no influence on the tack welding time and was therefore excluded from the time estimation formula (see Table 6.3). It was decided to keep the part thickness as a variable because it showed a marginal error increase.

5. The procedure was then repeated without NL as a variable to determine whether the remaining variables were relevant for estimating the tack welding time. Table 6.4 summarises the errors and action taken with the second iteration. The recorded data is given in Appendix E.

MLR with variables {W,L,NL,C,T}	**MLR with variables {L,NL,C,T}**	**MLR with variables {W,NL,C,T}**	**MLR with variables {W,L,C,T}**	**MLR with variables {W,L,NL,T}**	**MLR with variables {W,L,NL,C}**
31.2%	60.4%	71%	30.1%	46.5%	30.3%
Action taken	Keep W	Keep L	Exclude NL	Keep C	Keep T

Table 6.3 Errors obtained with initial MLR analysis and action taken

MLR with variables {W,L,C,T}	**MLR with variables {L,C,T}**	**MLR with variables {W,C,T}**	**MLR with variables {W,L,T}**	**MLR with variables {W,L,C}**
30.1%	46.8%	51.6%	37.6%	36.8%
Action taken	Keep W	Keep L	Keep C	Keep T

Table 6.4 Errors obtained with second MLR analysis and action taken.

The errors given in Table 6.4 are all bigger than the error of the first column. This therefore indicate that the part weight, length of joining line, part curvature and material thickness have an influence on the tack welding time.

The equation used to estimate the tack welding time is of the form:

Formula for Determining the Basic Assembly Time .

$$T = m_1 \cdot W + m_2 \cdot L + m_3 \cdot C + m_4 \cdot T + b$$

Where

W : Mass of the part (KG)
L : Length of joining lines (mm)
C=1 if part has in plane curvature else C=0
T :Thickness of plate material (mm)

The coefficients for the equation above are summarised in Table 6.5. These coefficients were the coefficients obtained with the MLR analysis that had part weight, length of joining line, part curvature and material thickness as variables.

Coefficient	m_1	m_2	m_3	m_4	b
Value	0.325	0.157	567	4.783	0
Units	$\frac{s}{kg}$	$\frac{s}{mm}$	[s]	$\frac{s}{mm}$	[s]

Table 6.5 Multiple linear regression coefficients

The basic tack welding time estimation with the coefficients listed in Table 6.5 gave the following errors. An average absolute error of 30% and a cumulative error of -2% for the recorded data. The standard deviation of the error was 36.23%. Statistical analysis shows, with a confidence of 90%, that the error would be less than -1%±7% for individual component tack welding. The error distribution is shown in Figure 6.2.

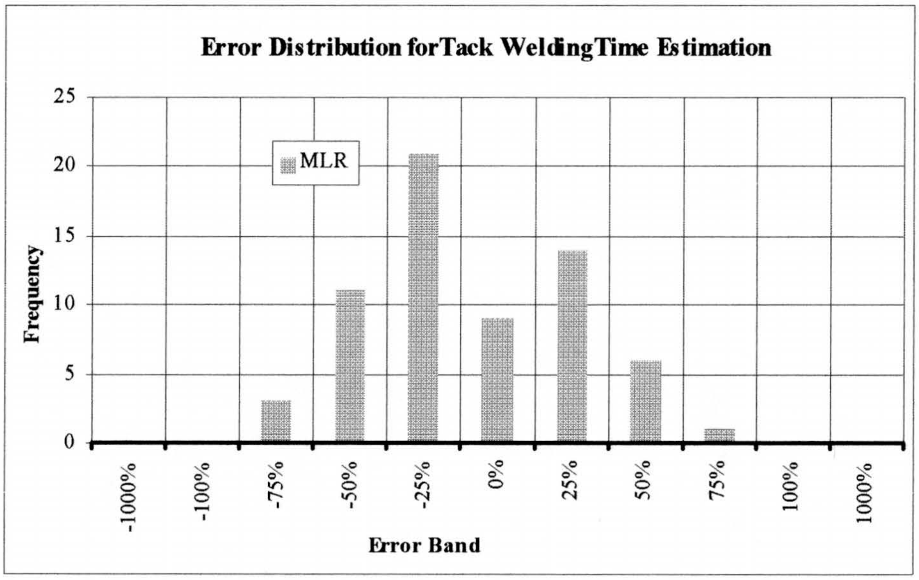

Figure 6.2 Error distribution for tack welding time estimation

6.6. Estimating the Basic Tack Welding Time

The time estimation model uses the coefficients of Table 6.5 to estimate the tack welding time per part. Additional trimming time can also be added to total tack welding time.

The basic tack welding time estimation formula are presented in Table 6.6. This formula estimates the tack welding time per part. The additional trimming time correction estimates the additional time that may be required for the whole assembly.

Tack Welding Time			
Description	**Formula**	**Unit**	**Variable Declaration**
Basic tack welding time	$O_p \cdot (0.325 \cdot w + 0.157 \cdot L + 567 \cdot C + 4.783 \cdot T)$	s	W : Weight of part [kg] $0.2 \leq w \leq 13190$ L : Length of joining line [mm] $127 \leq L \leq 11132$ T : Material Thickness [mm] C=1 if part has in plane curve else C=0 O_p=2 if only one operator[5] is working else O_p =1
Additional trimming time	$Tbasic \cdot 0.274$	s	Tbasic : Basic assembly time [s]

Table 6.6 Tack welding time estimation formulas

The designer will therefore see, with the use of this procedure, that the assembly time is, firstly, closely related to the number of parts and secondly to the “assemblability” of each part.

[5] The data was recorded with two operators working

7. Welding Production Time Estimation

7.1. Overview of the Flux Core Arc Welding Process

The self-shielded flux-cored arc welding process is an outgrowth of shielded metal arc welding. The main difference between shielded metal arc welding (MAG/MIG) and flux-cored welding is the electrode used. Solid electrode wires for MIG welding are drawn from billets of the proper physical composition, which may not be readily available.

The fabrication of flux cored electrodes begins with the slitting of coiled sheet into strips. These strips are then passed through rollers that form them into U-shaped cross sections. In the same operation, the formed strip is filled with a measured amount of core ingredients. The U-shaped strip is then passed through closing rolls, forming it into a tube and tightly compressing the granular core material. The round tube is then passed through drawing dies that further reduce the diameter and at the same time compresses the core ingredients to prevent any movement within the tube. In the case of flux cored wires, the special alloying elements are introduced in the core material to provide the proper deposit analysis. The cored production method provides a latitude of composition which is not limited to the analysis of steel billets available. Cored wires are also easier to use than solid wires of the same deposit analysis. The equipment used when welding with flux cored wires is the same as the equipment used for MIG/MAG welding. The flux cored wires can contain additional self shielding gas forming elements in the core to ensure a better quality weld. These self shielding elements are usually supplemented with external protective gas shielding such as CO_2 or CO_2-argon mixtures [Lincoln Electric, 1994].

7.2. Advantages and Disadvantages of FCAW

The main advantages of the flux cored arc welding process can be listed as follows [Cary, 1992; Salter, 1979]:

- High-quality weld metal deposit

- Excellent weld appearance : smooth, uniform welds
- Excellent contour of horizontal fillet welds
- Welds a variety of steels over a wide thickness range
- High operating factor : easily mechanised
- High deposition rate : high-current density
- Relatively high electrode metal utilisation
- Relatively high travel speeds
- Economical engineering joint designs
- Visible arc: easy to use
- Less pre-cleaning required than for metal arc welding because of the wide variety of flux core compositions
- Reduced distortion compared to shielded metal arc welding

The main limitations of the process can be listed as follows [Cary, 1992]:

- The process normally produces a slag covering that must be removed
- Flux-cored electrode wire is more expensive on a weight basis than solid electrode wires
- Flux-cored arc welding is only used for welding ferrous metals, primarily steel
- The general equipment for the process is expensive and requires more maintenance than the equipment used for manual metal arc welding. This is however more than compensated for by the high deposition rates and improved operating factor.
- Flux core arc welding generate more toxic gasses.

7.3. **Why Costing is Important**

7.3.1. ***Purposes of Costing***

The specific reason for costing of welding are varied, but are most often to [Lincoln Electric, 1994] :

- Provide data for bidding on a job.

- Compare the economics of welding to other methods of fabrication or manufacturing.
- Establish information required in making a decision between alternate designs.
- Evaluate proposed changes to welding procedures.
- Compare the economic advantages of competing welding processes.

When doing cost estimation for welding one needs to differentiate between the cost of weldment versus the cost of a specific weld section. The cost of weldments is good for comparing welding cost versus other processes of fabrication, such as casting. The cost of weldment includes [Cary, 1992] :

1. The cost of the weld.
2. The cost of material required.
3. The cost of part and joint preparation.
4. And the post-weld heat treatment required.

The cost of a specific weld section will give a good comparison between costs of competing welding processes.

Cost analysis for welded structures is a basic prelude to cost-reduction because it will show up wastes in the design, shop practices and the use of personnel [Lincoln Electric, 1994]. Cost analysis also point out excesses in weld sizes, root openings, root faces, included angles and reinforcements. All of these increase the overall welding costs substantially while giving the consumer of the product no value.

7.3.2. ***The Designer's Efforts for Cost Reduction***

Designers who are conscious of the cost of welding will firstly attempt to minimise the amount of weld metal required for a specific weld joint or weld section [Lincoln Electric]. Designers will also try to use more subtle changes, such as changes to eliminate a weld section, by making more use of pre-forming processes such as plate bending. A few points for the designer to keep in mind when specifying a weld joint are [Lincoln Electric, 1994]:

- Make sure that the weld material used serves an engineering function. For example, avoid the use of unequal leg sizes in fillet welds and make use of intermittent weld sections instead of continuous weld sections.
- Avoid specifying high-strength weld metal on other than primary load-carrying welds when joining high strength materials.
- Avoid unnecessary use of the all-around symbol.
- Consider deep penetration processes such as flux core arc welding instead of solid wire welding in order to reduce the volume of weld metal required for a specific strength in the joint. This will also decrease the cost of bevelling.

7.4. **Current Costing Procedures**

Costing procedures for welded structures currently in use mainly gives a cost estimation for welding as a cost per unit length of weld [Cary, 1992; Lincoln Electric, 1994; Phelps,1991]. The cost estimates of these procedures are also highly dependent on the operating factor specified by the designers, something which they seldom know. Secondary welding tasks such as fettling, set-up, de-set-up, and preheating are taken as factors of the arc time.

None of the models studied made electrode or labour allowances for post weld treatment, such as back gouging, back grinding and surface finish requirements which are set by the designer. These procedures also neglect electrode change time for semi-automatic welding processes.

7.5. **Time Estimation for Flux Core Arc Welding**

The total time required for flux core arc welding is broken down into smaller time elements. These time elements are related to specific operator tasks. Each time element is calculated and combined in a proper manner with the other time elements.

Electrode manufacturer data was also used in order to make the model more general when estimating certain factors related to the electrode.

7.6. **Model Construction**

7.6.1. ***Function Definition***

The main focus was to determine the welding time and weld metal required as early as possible in the design, so that the designer can identify high cost areas. This will allow the designer to optimise the product before it has gone into a prototype or production phase thus saving greatly on the costs of development.

The model will also give the designer the ability to check the production time allocation for every weld section individually, thus allowing a cost to be established for each weld section as well as its contribution to the total cost of welding. The model will also portray the increase in welding cost of weld sections which require back gouging, back grinding, blend grinding and polishing.

The primary costs of welding depicted in this analysis are [Lincoln Electric, 1994; Phelps, 1990; Sim, 1991] :

1. Consumable costs
2. Labour cost
3. Power cost
4. Gas Cost

Other cost elements such as equipment and overhead cost, which are not part of the direct manufacturing cost, can be defined as a factor of the labour costs.

7.6.2. ***Consumable Costs***

Consumable costs, for flux core arc welding, can be divided into two categories:

1. Electrode cost
2. Shielding gas cost.

The electrode cost is determined by :

1. The volume of metal required to fill a certain weld joint design. This is normally determined by the cross sectional area and the length of the weld section. Thus by minimising the cross sectional area and length the volume of metal required will be minimised. The area can be minimised by using thinner plate thickness thus allowing the use of grooved joint design over a bevelled joint design. The use of a double-V joint design over a given plate thickness will use less filler metal (reducing filler metal required ±0.5 times) than a single-V design over the same thickness of plate. It is also important that root openings on any weld joint design be kept to a minimum [Lincoln Electric, 1994]. Figure 7.1 illustrates the break even production time for a 1 meter 30 and 45 degree included angle V-type joint design. A deposition rate of 3.67kg/hr was used (typical 1.6mm wire deposition rate). Back gouging and part handling were also included for the double-V joint design.
2. The yield factor of the electrode used. Flux core arc welding electrodes yield factors are in the range of 80-85% (ratio of weight of metal in wire to total wire weight) with an additional spatter loss of 5%. Recent developed flux core wires introduced metal powder in the flux of the electrode which increases the yield factor and hence the deposition rate. Increasing the welding current will increase spatter loss. Spatter loss can, however, be considered as negligible. The combined effect of spatter loss and filler metal yield is known as the deposition efficiency (ratio of weld metal deposited to weight of wire purchased). Therefore the deposition efficiency of flux core arc welding electrode is in the range of 75-85%.

3. The quality of weld specified e.g.-whether it is specified that a weld has to be back gouged and back ground in order to ensure a full penetration high quality weld. The volume of metal needed to fill the weld section, will then increase proportionally to the amount of gouging that has taken place and to a much lesser extent, the amount of back grinding required.

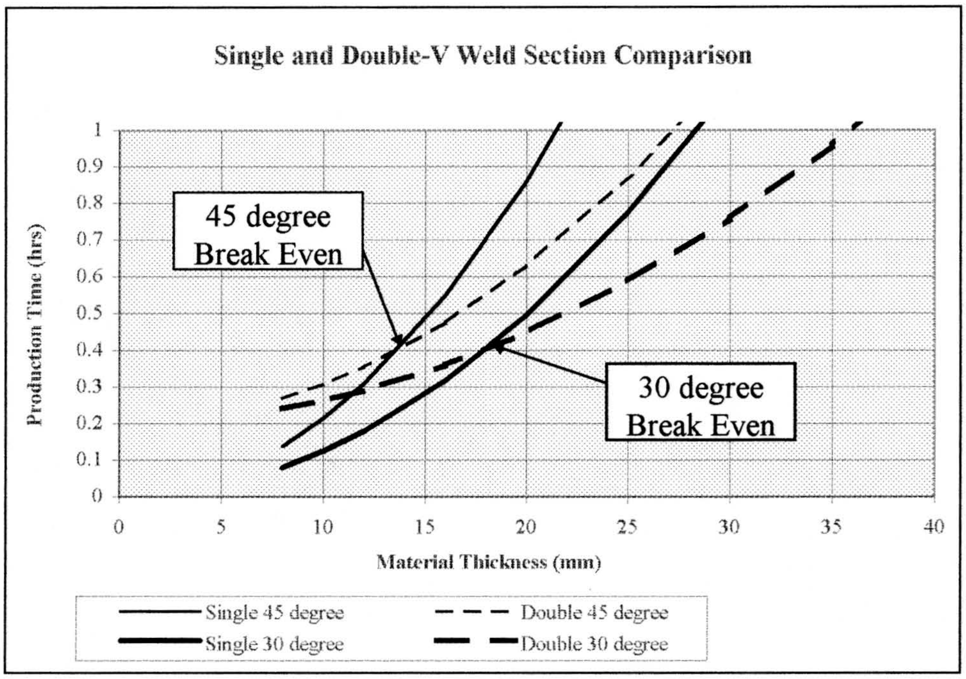

Figure 7.1 Single-V and double-V weld section comparison

The shielding gas cost is generally considered to be negligible and previous studies have shown that the gas component is approximately 7% of the total cost [Phelps, 1990]. The shielding gas required is directly proportional to the gas flow required for the electrode and the arc time required to complete a weld section [Lincoln Electric, 1994]. Gas flow rates are dependent on the environment (air movement in workshop, welding nozzle diameter and nozzle distance form work) in which welding takes place and ranges mainly between 0.991m^3/hour to 1.274 m^3/hour for flux cored electrodes [Lincoln Electric, 1994]. Extreme cases of outdoor welding with a long electrode stick-out may require gas flow rates of up to 1.557 cubic meters per hour.

7.6.3. ***Procedure for Estimating the Electrode Required***

The cost estimation model calculates the cross sectional area of the weld section, multiplied by its length to determine the minimum deposited volume. The deposited mass can then be obtained by multiplying the volume with the density of steel. The weight of metal is then divided by the deposition efficiency of the electrode to determine the minimum amount of electrode that will be consumed. The model then uses recorded data to determine the volume of additional weld metal required if the weld section(s) are to be back gouged (see ***Back Gouge Time Estimation*** op page 132).

7.6.4. ***Labour Cost***

Labour costs are influenced by design related parameters and management related parameters which have an affect on the welding time.

7.6.4.1. Parameters Affecting Labour Time

Design related parameters can be summarised as follows [Reynolds, 1991, Mills, 1992]:

- The number of weld sections in an assembly or sub-assembly. The larger the weld section count the longer it will take to weld the assembly.
- The size and length of each weld section. Large weld sections with a length that falls within the normal reach of a welding operator will yield good operating factors while long weld sections will require the operator to reposition himself more often and hence increase the total welding time with a slight increase in the operating factor.
- The accessibility of each weld section. Welds with a good accessibility reduce fatigue of the welding operator and increases the normal welding reach to a maximum, and hence increase in the operating factor.
- The type of electrode to be used. Manufacturers use thicker electrodes as a means of reducing the arc time by increasing the deposition rate.
- Preheat requirements that need to be employed in order to produce a

quality weld. The higher the preheat requirements the longer it will take to complete a weld section. The preheat time is directly influenced by the volume of material and material composition, thicker material sections will take longer to preheat and the method of preheating (electric/flame).

- Weld quality specification, for example, when all weld sections on an assembly must be back gouged and back ground to ensure a full penetration weld without any flux inclusions, or when a weld section must be blend ground and polished in order to remove stress concentrations. These additional operations increase the production time and the required weld metal considerably.
- Weld joint specification. The preparation, cutting and cleaning of the edges of the material to be welded, is an integral and very important part of the costs associated with the welded joint. See the section of weld joint preparation (4.1.1 on page 48).

Management related parameters can be summarised as follows :

- Motivation of the welding operator.
- Working environment of operator: poor shop floor facilities and fatigue causing conditions such as high temperatures, noise, etc.
- The availability, quality and reliability of equipment that the operator uses.
- The electrode diameter that is being used.
- The weight of electrode packages purchased i.e. 15kg wire packs or 30kg wire packs.
- Inadequate training of welding operators.
- Multi-tasking of welding operators.
- Poor maintenance of welding machines.
- Excessive handling of material.

All the above mentioned parameters have a direct influence on the overall time required to complete a weld section.

7.6.4.2. Labour Time Elements

The labour time required to complete a weld section can be divided into the following time elements :

1. Preheating time
2. Arc time
3. Fettling time
4. Set-up and De-Set-up time
5. Back gouging and finishing time
6. Electrode change time

The total estimated welding time is then a summation of the above mentioned time elements.

7.6.4.3. Determining the Preheating Time

7.6.4.3.1. *Why Preheating*

Preheating is mainly used for one of the following reasons [Lincoln Electric; 1994]:

1. To reduce shrinkage stresses in the weld and adjacent base metal.
2. To provide a slower rate of cooling through the critical range (871°C-721°C), preventing excessive hardening and lowering the ductility of both the weld and the heat-affected area of the base plate.
3. To provide a slower rate of cooling through the 204°C range, allowing more time for any hydrogen that is present to diffuse away from the weld and adjacent plates to avoid underbead cracking.

The amount of preheat required for any application depends on the base metal composition, plate thickness and heat input of the process. Unfortunately there is no method for metering the heat input for an assembly with a pre-heating torch. Operators usually start preheating the joint and the adjacent area and measure the surface temperature at regular intervals with a crayon marker, which changes colour when the desired surface temperature is reached. These crayon marks should change colour when applied to the preheated area for the total duration of welding.

Preheating is very important because it is known from experience that field or even shop repairs of a crack is more costly than the cost of preheating [Lincoln Electric,1994; Salter, 1979]. It is also recommended that once an assembly has been preheated, the weld section must be completed in order to prevent a second preheat operation.

7.6.4.3.2. *Estimating the Preheating Temperature*

There are various guides which may be used to determine the preheat temperatures, including the recommendation of the steel manufacturer. Generally, the higher the carbon content of a steel, the lower the critical cooling rate and the greater the necessity for preheating and the use of low hydrogen electrodes. Carbon is not the only element that influences the critical cooling rate. Other elements in the steel are also responsible for a loss in ductility and an increased hardening that occurs with rapid cooling. Therefore, one has to consider total hardenability to determine the preheating requirements.

Carbon equivalents (C_{eq}) are empirical values, determined by various carbon-equivalent formulas that represent the sum of the effects of various elements in steel on its hardenability. The International Institute of Welding (IIW) carbon equivalent equation for estimating the preheat temperature is [Lincoln Electric, 1994]:

Carbon Equivalent Equation .

$$Ceq = \%C + \frac{\%Mn}{6} + \frac{\%Ni}{15} + \frac{\%Mo}{5} + \frac{\%Cr}{5} + \frac{\%Cu}{15} + \frac{\%V}{5}$$

This formula is valid only if the alloy contents are less than the following:

$\%C \leq 0.5\%$	$\%Mo \leq 0.6\%$
$\%Mn \leq 1.6\%$	$\%Cu \leq 1\%$
$\%Ni \leq 3.5\%$	$\%Cr \leq 1\%$

The approximate preheat temperatures are then :

$Ceq < 0.45\%$	Preheat is optional .
$0.45\% < Ceq < 0.6\%$	Preheat 95-205 degrees Centigrade
$0.6\% < Ceq$	Preheat 205-705 degrees Centigrade

7.6.4.3.3. *Preheating Time Estimation*

The time estimation model relates the time needed for preheating to the volume of steel, the pre-determined preheat temperature and the heating torch output. This is by no means very accurate but will show the benefit of using different material thickness and material composition.

The time estimation model relates the heat energy input to the volume of material that needs to be preheated around the weld section. Data for the heat output of heating torches can be obtained from the Afrox product catalogue. The catalogue, however, warns against the use of these values since these will vary considerably with flame settings, regulator pressures and the use of different heating nozzles. The heat output values vary in the range of 76000 kJ/hr to 652000 kJ/hr for the different types of heating nozzles [Affrox, 1996]. The time estimation model uses a specific heat constant of 451 J/kg/K and a steel density of $7836 kg/m^3$, which is the average for carbon steels [Mills, 1992]. An average of the heat output given by the Afrox data, 270000kJ/s, is used in the time estimation model for the heating torch heat output.

7.6.4.3.4. *Procedure for Estimating the Preheating Time*

Preheating Time Estimation .

Definition of Constants .

$$C_{steel} = 451 \cdot \frac{J}{kg \cdot K}$$

$$\rho_{steel} = 7836 \frac{kg}{m^3}$$

$$H_{torch} = 75 \cdot \frac{kJ}{s}$$

$$\eta = 0.25$$

Formula for Determining the Preheat Time.

$$PreheatTime = \left[\frac{Vol \cdot \rho_{steel} \cdot C_{steel} \cdot \left(T_{preheat} - 15 \right)}{H_{torch} \cdot \eta \cdot 1000} \right] \cdot sec$$

Where

Vol : Volume of steel to be preheated (m^3)
ρ : Density of steel (kg/m ^{3})
C : Specific heat of steel (J/(kg.K))
T : Required preheat temperature (degrees centigrade)
H : Heat input per unit time for torch (kJ/s)
η : Heat transfer efficiency

7.6.4.4. Determining the Arc Time

7.6.4.4.1. *Deposition Rate and Operating Factor*

The operating factor is defined as the ratio of the time that the welding arc is on, to the time actually paid for welding [Lincoln Electric, 1994; Reynolds, 1991]. The operating factor should be closely considered along with the deposition rate of the welding process being used. A low deposition rate with a high operating factor can yield the same result as a low operating factor with a high deposition rate. Therefore, both must be optimised in order to obtain the best results.

The deposition rate is dependent upon the wire properties and welding process. The operating factor is dependent on the operator, the environment in which the operator works and the welding process being used.

Figure 7.2 shows the effect of welding environment on the operating factor. Figure 7.3 shows the operating factor dependability on the welding process. Figure 7.4 shows the minimum and maximum deposition rate dependability for a number of welding processes.

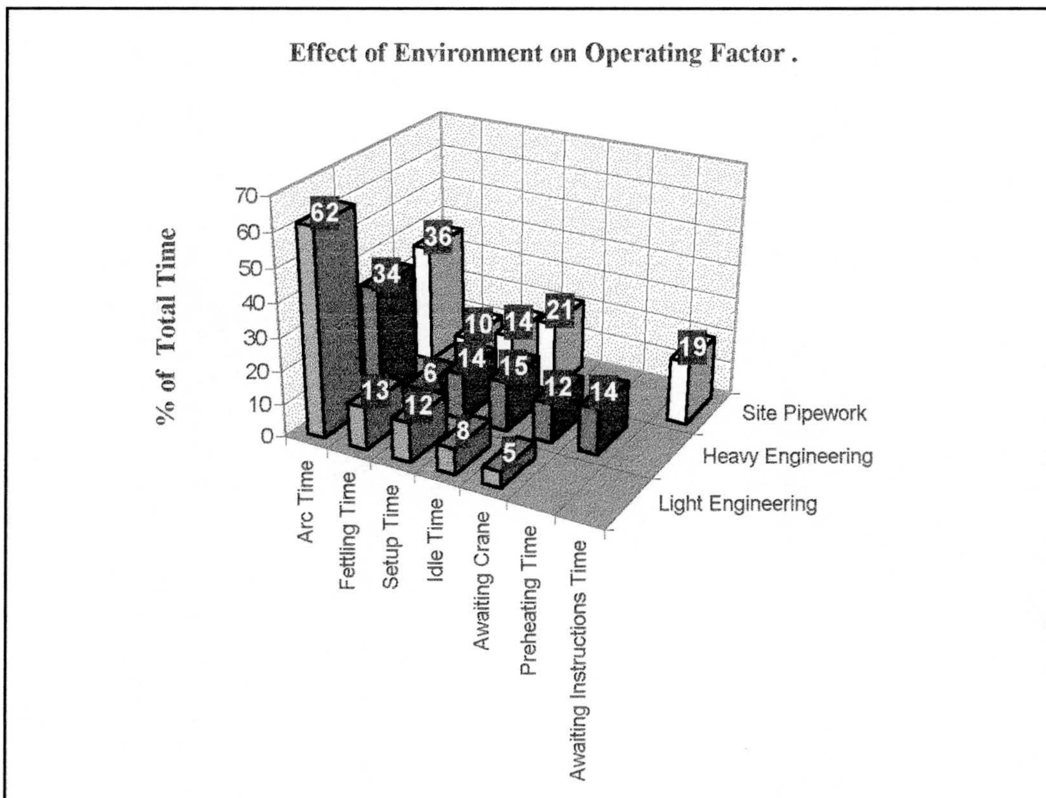

Figure 7.2 Typical time elements for different manufacturing environments [Salter, 1979]

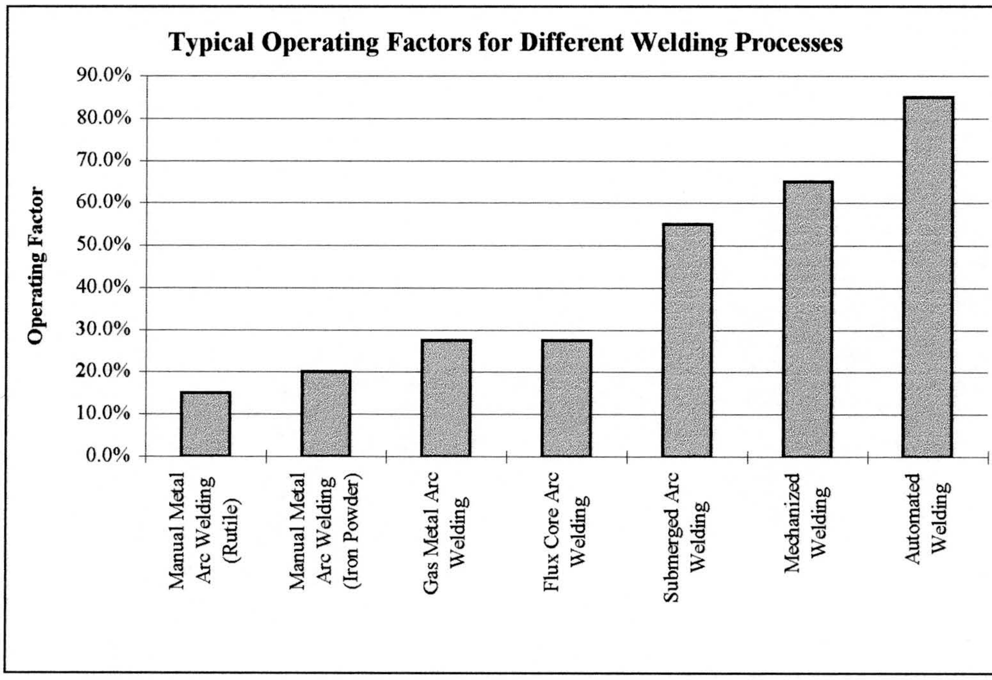

Figure 7.3 Typical operating factors for different welding processes [Phelps, 1990]

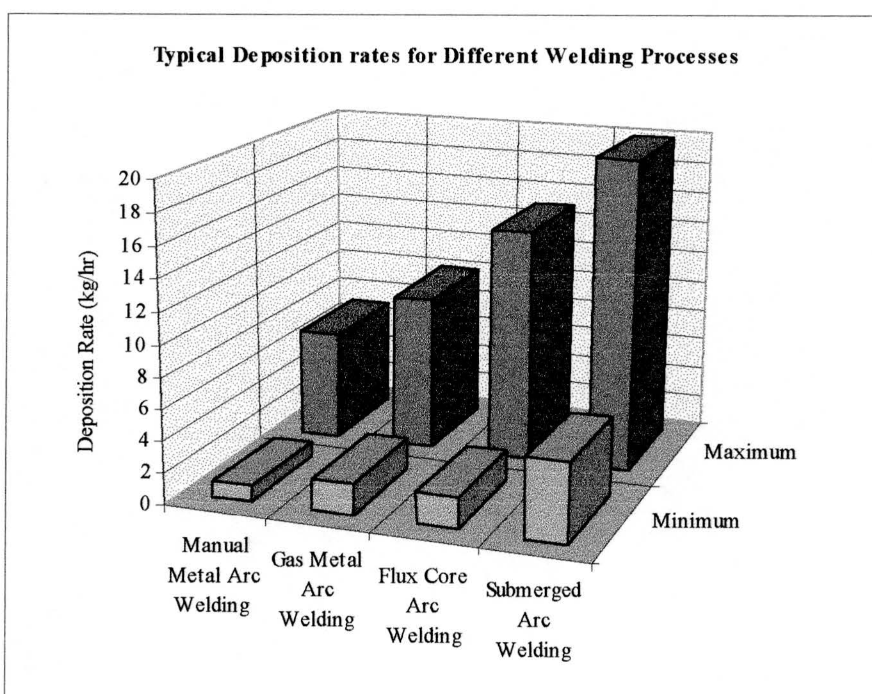

Figure 7.4 Typical deposition rates for different welding processes [Phelps, 1990]

7.6.4.4.2. *Estimating the Deposition Rate*

The arc time is determined by making use of the direct relationship between the wire feed speed and the welding current (deposition rate) when a constant potential drop across the arc and electrode extension is used. The voltage between the part and the contact tip of the welding nozzle consists out of two voltage drops. A voltage drop across the arc, which stays more or less constant, and a voltage drop across the electrode stick-out.

If the electrode stick-out increases with a fixed wire feed speed, then the welding current drops because the voltage drop across the electrode stick-out increases, this will result in more preheating of the electrode stick-out and less preheating of the base metal, which will reduce the penetration of the weld section. The opposite will happen if the stick-out shortens with a constant wire feed speed and constant voltage drop.

One must also be aware of the different modes of metal transfer across the arc, globular and spray transfer. The deposition rate differs for these two types of transfer and it is also known that they are dependent on the welding current being used. Fortunately we can assume spray transfer for flux core wires for a wide range of current settings.

The model uses welding current to determine the deposition rate. This is mainly because electrode manufacturers give welding current vs. deposition relationships for their electrodes. Some manufacturers specify this relationship as welding current vs. wire feed speed, in which case the engineer can calculate the deposition rate. Electrode manufacturers furthermore also give optimum welding settings for their electrodes which makes the electrode information needed to calculate the arc time complete [Alloy Rods, 1994; Cary, 1992; Speedarc Guidelines, 1997; Wasa Product Catalogue, 1997].

It can be assumed that the deposition rate vs. current relation follows an almost linear trend for a specific manufacturer and electrode diameter. The literature review showed that the variation of deposition rate vs. current settings is minimal when considering the same classification of electrode but different manufacturer [Nichols, 1991; Salter, 1997] . The variation becomes more visible when one looks at the same composition of electrode but different wire diameters [Nichols, 1991]. These relationships eases the use of such a formula and keeps calculation simple. Therefore when the welding current is fixed, the wire feed speed is fixed and hence the deposition rate is fixed.

Welding settings were recorded under normal working conditions to determine a comparison between manufacturer specified settings and actual shop settings.

Welding Current Setting for 1.6 mm flux core arc welding electrode @ 268 Ampere

- The welding current was taken as the median of the recorded data. Statistical analysis shows, with a confidence of 90%, that the current setting would be between 268A±10.97A. This is 8A higher than the suggested ampere setting by the manufacturer [Alloy Rods, 1994]. See Appendix F.1.6 page F-XIII to F-XIV

Therefore, when choosing a welding electrode, the designer simply needs to express the deposition rate of the electrode as a function of the welding current [Alloy Rods, 1994; Cary, 1992; Speedarc Guidelines, 1997; Wasa Product Catalogue, 1997].

7.6.4.4.3. *Procedure for the Welding Arc Time Estimation*

Formula for Determining the Arc Time of a Weld Section

$$\mathrm{DepositionRate} = (m \cdot I + c) \cdot \frac{kg}{hr}$$

Where

I : Welding current (average values or suggested values from manufacturer) (A)
m : Slope of dep. rate vs. welding current line for the specific electrode being used
c : Constant of dep rate vs. welding current line for the specific electrode being used

$$T\_Arc = \left(\frac{Vol \cdot \rho_{steel}}{\mathrm{DepositionRate}} \cdot 3600 \right) \cdot sec$$

Where

Vol : Volume of metal required to complete the weld section (m^3)

7.6.4.5. Determining the Fettling Time

Multi-pass welding with flux core arc wire requires inter-pass cleaning to ensure that no slag inclusions occur in the weld section. In general it was found that the welding operators weld one run and directly afterwards clean the slag from the weld section. The cleaning time is therefore related to the number of weld runs required to complete the weld section and to the length of the weld section. The number of weld runs required can, therefore, be determined by dividing the total cross section area of the weld by the area covered per weld run which is primarily related to the electrode diameter. The size of weld bead and hence the area covered with one pass will differ from welding operator to welding operator but there is a general trend for weld area vs. weld runs required [Harnisfeger, 1998].

7.6.4.5.1. *Constants for Welding Fettling Time*

Data for three different diameter electrodes were recorded. The data was also recorded for two different electrode manufacturers under normal welding conditions. Recorded data for flat and horizontal position welding were mixed in order to get a more general value for the area covered per run. The following results were obtained:

Area Covered with 1.2mm Flux Core Wire = 21.3 mm^2 per run

Statistical method used to obtain constant	Median of recorded data
Average absolute error	13%
Cumulative error	4%
Standard deviation the error	20%
Lower confidence limit of 90%	-11%
Upper confidence limit of 90%	11%
Reference	Appendix F.1.1.1 page F-II

Table 7.1 Properties of area covered with 1.2mm wire

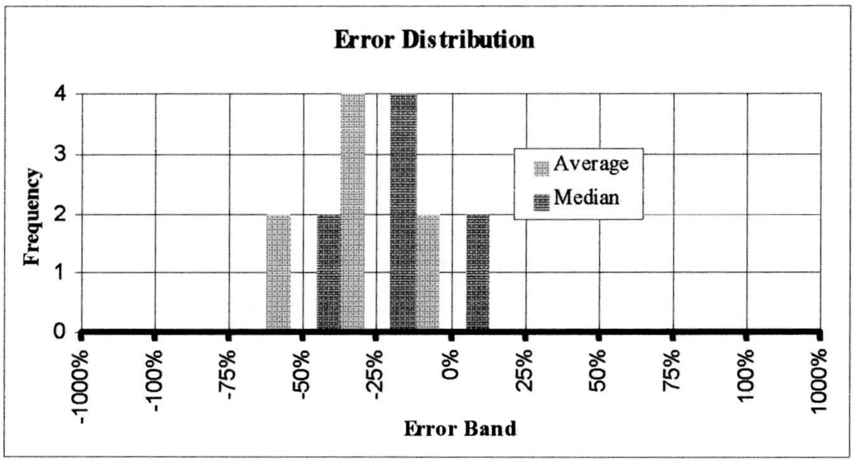

Figure 7.5 Error distribution for estimating single run area of 1.2mm wire

Area Covered with 1.6mm Flux Core Wire = 25 mm^2 per run

Statistical method used to obtain constant	Median of recorded data
Average absolute error	15%
Cumulative error	-3%
Standard deviation the error	28%
Lower confidence limit of 90%	-12%
Upper confidence limit of 90%	12%
Reference	Appendix F.1.1.2 page F-III

Table 7.2 Properties for area covered with 1.6mm wire

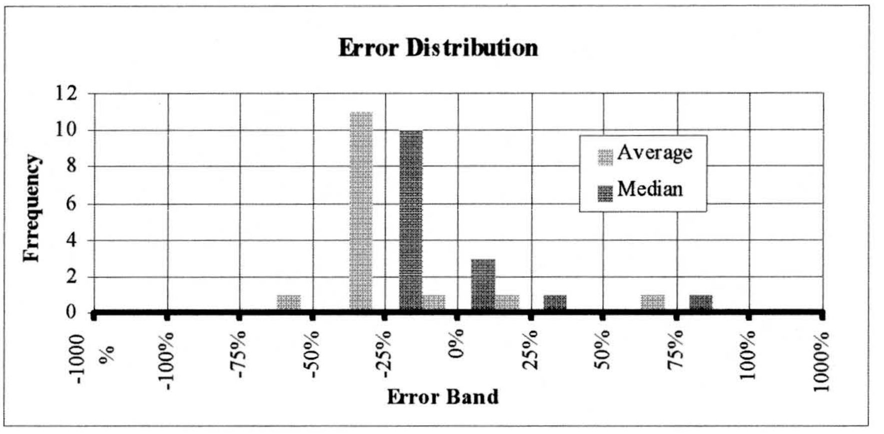

Figure 7.6 Error distribution for estimating the single run area of 1.6mm wire

Area Covered with 2.4mm Flux Core Wire = 32.8 mm^2 per run

Statistical method used to obtain constant	Median of recorded data
Average absolute error	23%
Cumulative error	4%
Standard deviation the error	34%
Lower confidence limit of 90%	-11%
Upper confidence limit of 90%	11%
Reference	Appendix F.1.1.3 page F-V

Table 7.3 Properties of area covered with 2.4mm wire

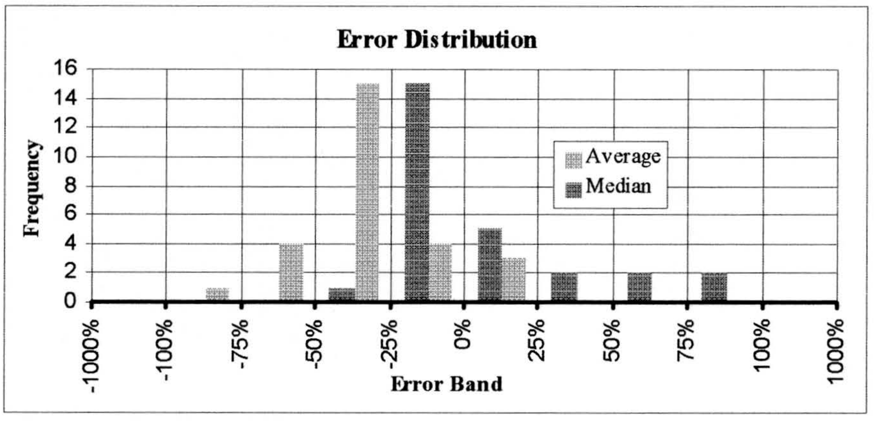

Figure 7.7 Error distribution for estimating the single run area of 2.4mm wire

Fettling Speed for one weld run = 878 mm per minute

Definition:

The fettling time is defined as the weld run length divided by the fettling speed.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	49%
Cumulative error	2%
Standard deviation the error	72%
Lower confidence limit of 90%	-24%
Upper confidence limit of 90%	24%
Reference	Appendix F.1.2 page F-VI

Table 7.4 Properties of fettling time element

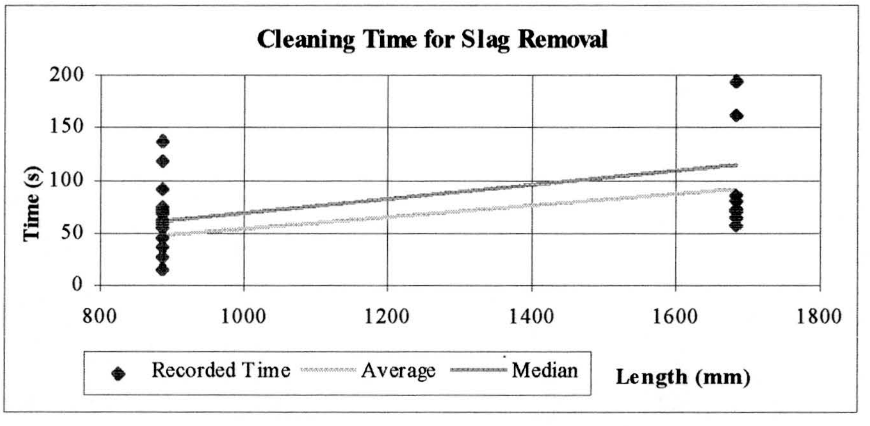

Figure 7.8 Fettling time vs. weld length for FCAW

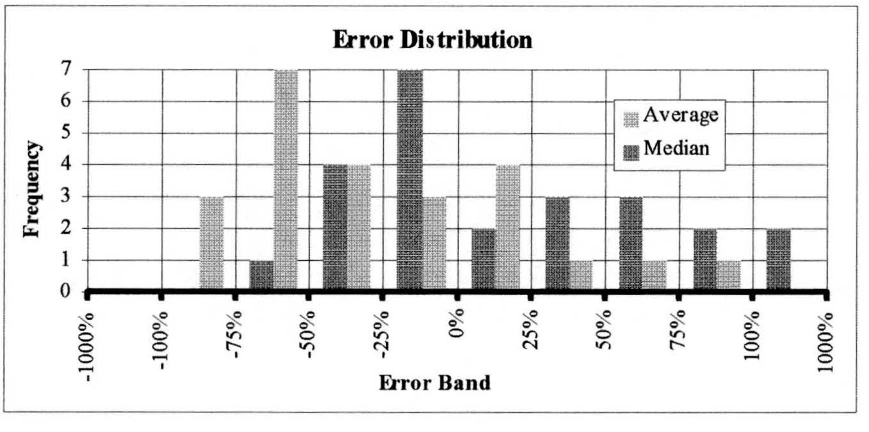

Figure 7.9 Error distribution for estimating the fettling time

7.6.4.5.2. *Procedure for Estimating the Fettling Time of a Weld Section*

The time formulas presented in Table 7.5 estimate fettling time per weld section. The term "*AreaCoveredPerRun*" in Table 7.5 refers to the constants given in paragraph 7.6.4.5.1. The formulas were constructed with the aid of the process flow diagram for flux core arc welding, Figure 7.10. The fettling time element occurs for every weld run.

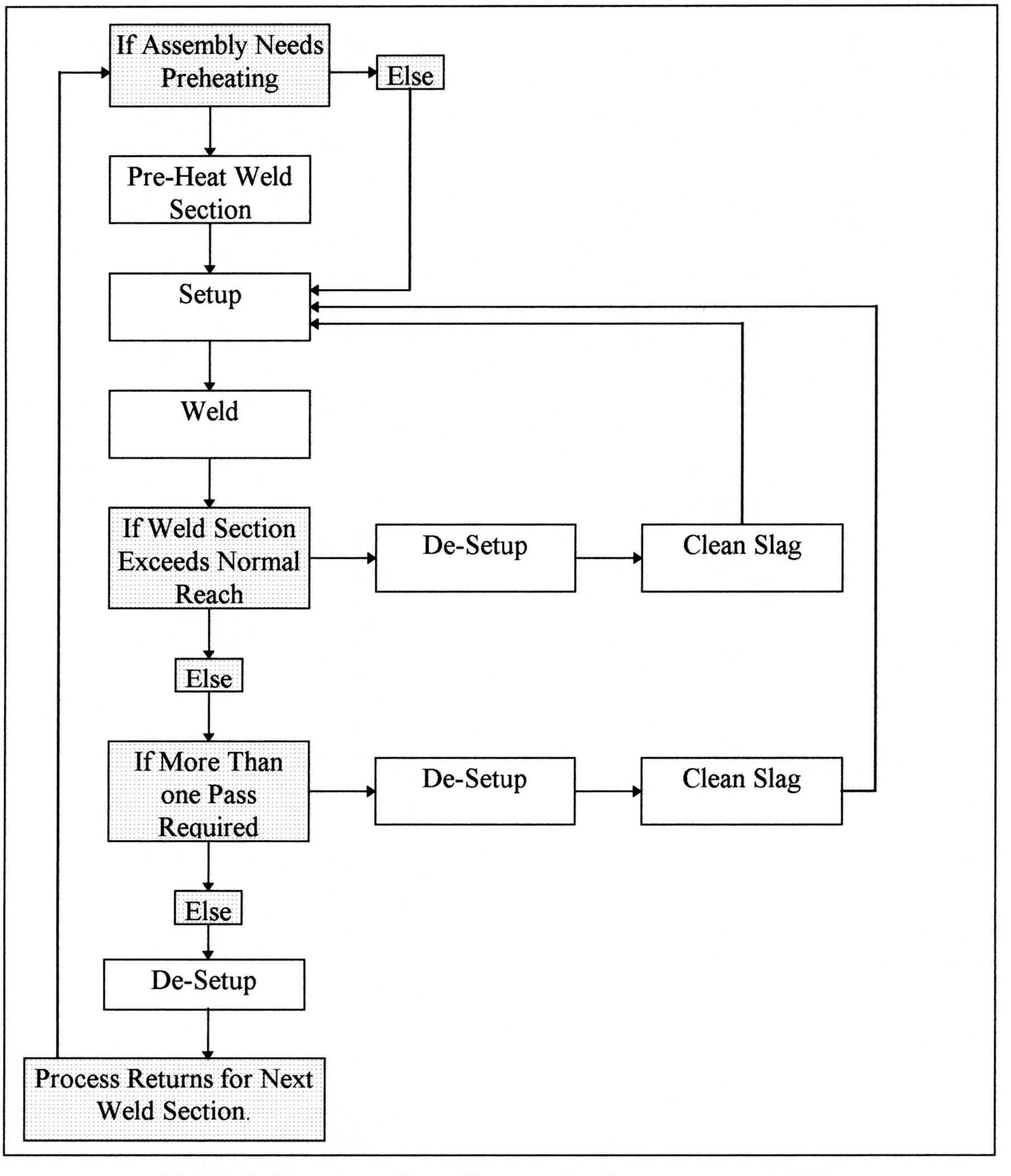

Figure 7.10 process flow diagram for flux core arc welding

Description	Constant/Formula	Unit	Variable Declaration
Runs	$round\left(\frac{A}{AreaCoveredPerRun}\right)$		A : Cross sectional area of weld section [mm^2]
Fettling Time	$\frac{Runs \cdot L}{878} \cdot 60$	s	L : Length of weld section [mm]

Table 7.5 Fettling time estimation formulas

7.6.4.6. Determining the Set-up and De-Set-up Times

When a welding operator welds a long multi-pass weld section, he has to stop welding in between runs or after he has reached his normal reach. This means that the welding operator has to set-up himself and de-set-up himself after each interval. The welding operators then cleans the slag from the new weld run and then commences with set-up. The set-up and de-set-up time, although small lengths of time, can contribute to a greater time element of a welders time when welding large multi pass weld sections.

The normal reach of welding operators was recorded for weld sections with good to poor accessibility. The accessibility was greatest when the weld section was about 900 mm from the ground and the welding operator did not have to bend over the work piece, in order to reach the weld section. The average normal reach for such weld sections was 1213 mm. The accessibility, for a weld section 900 mm from the ground but where the operator had to bend over the work piece in order to reach the section, was a bit more hindered and it was found to be 731 mm. When the weld section was on ground level and the welder had to kneel in order to do his work the normal reach was found to be 772 mm.

Because the designer will never know when a weld section will be welded at hip height or on ground level it was decided best to use an average value of the recorded data, for normal operator reach.

The set-up times for a welding operator does not include putting on all his protective clothing because this should only happen about four times a day, when the welder arrives at work and after each tea break. Set-up time is therefore defined as picking up the welding gun, positioning of the weld gun and welding operator, and lowering of the welding helmet until the arc is visible. The de-set-up times is considered in the same way and is defined as the time taken from when the arc stops to the time the welding operator starts cleaning the slag from the weld run.

7.6.4.6.1. *Constants for Welding Set-Up and De-Set-Up Time*

The Normal Reach, Set-up and De-Set-up times were recorded for different weld lengths and accessibility and it was found to be:

Welding Operator Set-up Time = 11 seconds

Definition:

Total time taken by operator to position himself, prepare welding nozzle, lower welding helmet and initialise arc.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	50%
Cumulative error	-19%
Standard deviation the error	61%
Lower confidence limit of 90%	-16%
Upper confidence limit of 90%	16%
Reference	Appendix F.1.3 page F-VII

Table 7.6 Properties of set-up time element

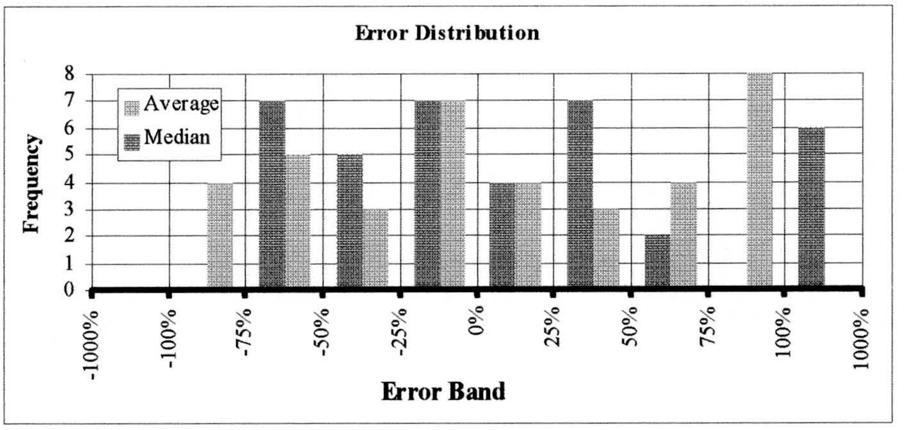

Figure 7.11 Error distribution for estimating the welding setup time

Welding Operator De-Set-up Time = 5 seconds

Definition:

Total time taken by operator to put welding nozzle down, lift welding helmet and pick up chipping hammer.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	40%
Cumulative error	3%
Standard deviation the error	53%
Lower confidence limit of 90%	-1%
Upper confidence limit of 90%	1%
Reference	Appendix F.1.4 page F-IX

Table 7.7 Properties of de-set-up time

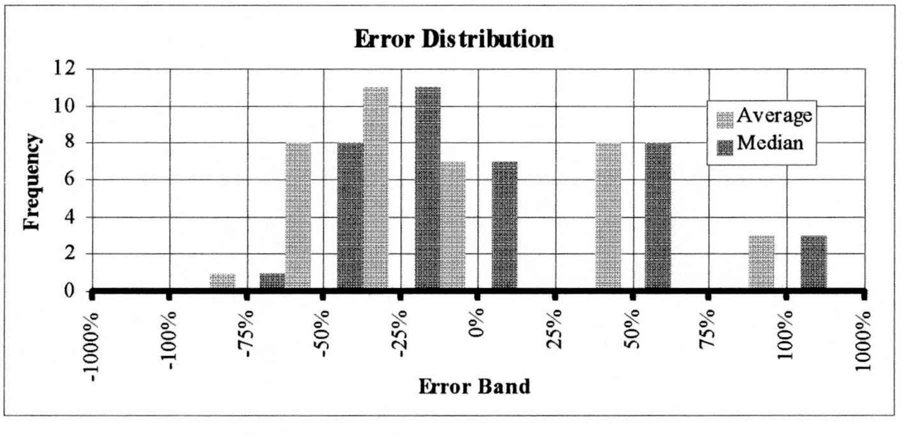

Figure 7.12 Error distribution for estimating the welder de-set-up time

Normal Reach of Welding Operator = 833 mm

Definition:

Average distance that an operator welds before he needs to reposition himself.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	31%
Cumulative error	-8%
Standard deviation the error	38%
Lower confidence limit of 90%	-6%
Upper confidence limit of 90%	-6%
Reference	Appendix F.1.5 page F-X

Table 7.8 Properties of normal reach constant

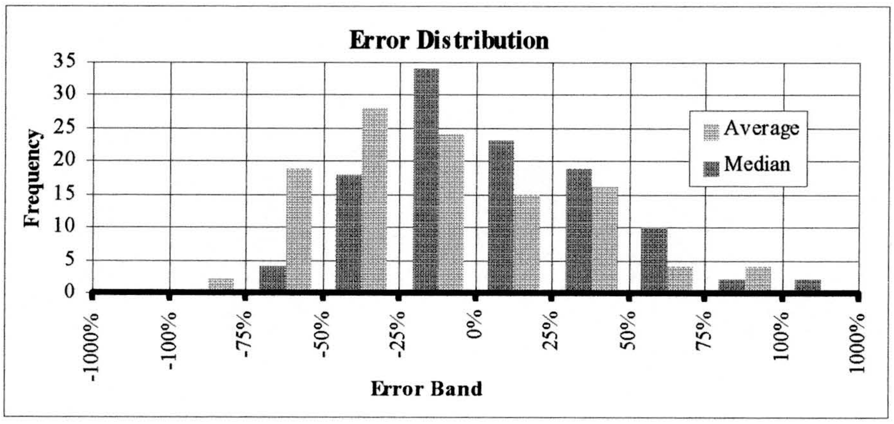

Figure 7.13 Error distribution for estimating the normal reach

7.6.4.6.2. *Procedure for weld Set-up and De-Set-up Time*

The time formulas presented in Table 7.9 estimate the set-up and de-set-up time per weld section. The term "*AreaCoveredPerRun*" in Table 7.9 refers to the constants given in paragraph 7.6.4.5.1. The weld set-up and de-set-up time elements occurs per weld run and per start stop sequence if the weld length is longer than the normal reach of the operator.

Description	Constant/Formula	Unit	Variable Declaration
Runs	$round\left(\frac{A}{AreaCoveredPerRun}\right)$		A : Cross sectional area of weld section[mm^2]
StartStop	$round\left(\frac{L}{833}\right)$		Rounding is to the higher integer
"Set-up" and "De-Set-up" Time	$Runs \cdot StartStop \cdot (11+5)$	s	

Table 7.9 Setup and de-set-up time estimation formulas

7.7. Additional Welding Related Times

7.7.1. *Back Gouge Time Estimation*

When a designer specifies a full penetration weld section, the manufacturing plant automatically assumes that it is a critical weld and that there must be no porosity or any such defects in the centre of the weld. This automatically implies that the welding operator will have to weld the weld section on one side, turn the assembly around, back gouge the weld section and then get a grinder to clean the surface of the back gouged section.

These operations, although very simple, take up a lot of production time, and must therefore be included as part of the total welding time. Back gouging and back grinding also has an affect on the amount of welding electrode that needs to be purchased because both these processes remove already deposited weld material from the weld section. It is known that when the electrode consumption for a specific weld joint design changes then the overall welding time and hence costs changes.

A basic analysis was done to determine the gouging time and the amount of material being removed. The gouging time can be determined by the gouging speed and the number of passes required to obtain the necessary depth. The gouging time is defined as the arc time, cleaning time and electrode change time, lumped together as one parameter. This makes the model simple and easy to use. A general electrode consumption was also obtained. Previous studies showed that the electrode consumption, gouge depth and gouge width will also differ from one diameter of electrode to another [Cary, 1992]. Different current settings will also have an effect on the amount of material removed per pass and the electrode consumption.

The number of passes required to obtain a certain depth and width was determined by gouging six test samples and recording the dimensions of the groove after each gouging pass. The process was performed by an operator who was familiar with the gouging procedure. It was stated to the operator that the groove must be gouged in such a way that he will have to be able to weld it afterwards.

From Table 7.10, it can be seen that the first three depths can be obtained by successive gouging passes. To obtain a depth deeper than the third depth the operator had to gouge three passes in order to obtain accessibility if he wanted to weld it afterwards. Successive gouge depths all required three passes more for the same reason.

The groove took on the shape of a parabola and hence the area could be determined from the depth and width of the groove. The areas removed per pass are summarised in Table 7.11.

Gouging passes required	Average Depth (mm)	Average Width (mm)	Median Depth (mm)	Median Width (mm)
1	6.5	12	6.5	13
2	11.	13	11	13.5
3	16.	19	16.5	19.5
6	25.5	25	25.5	25
9	36.5	30	35.5	30
12	43.6	30	44.5	30

Table 7.10 Gouging depth and width given as average and median values (see Appendix F.2.1)

Average Area Removed Per Pass	101.96	mm^2
Median Area Removed Per Pass	102.58	mm^2

Table 7.11 Area removed per gouging pass (see Appendix F.2.2)

The average and median areas removed per pass gave an average absolute error of 12% and a cumulative error of 9% for the recorded data when used to estimate the total area removed. The standard deviation of the error was 20%. Statistical analysis shows, with a confidence of 90%, that the error would be less than 0%±5%.

The user of the model can determine the number of gouging passes required directly from Table 7.10. The total cross sectional area removed can then be determined by multiplying the number of gouge passes with the average area removed per pass.

The time study for back gouging showed that the production time estimation for back gouging can be broken down into the following time elements.

1. Set-up and De-Set-up.
2. Gouging Time

The total time estimation is a combination of the above mentioned time elements.

7.7.1.1. Constants for the Back Gouging Time

The following constants were determined from the time study data under normal working conditions:

Gouging Set-up = 55 seconds

Gouging De-Set-up = 12 seconds

- Set-up and De-Set-up for gouging occurs only once for every weld section. Only three set-up and de-set-up points were recorded and can be considered as negligible because this is a very small element of the total time (Appendix F.2.3 & F.2.4).

Gouging Time = $0.272 \cdot L + 135$ seconds

Definition:

Total time taken by operator to gouge a weld section of specified length with one gouging pass (electrode changes included).

Statistical method used to obtain formula	Least square fit method [6]
Correlation coefficient	0.989
Valid range for formula	$380 \leq L \leq 10200$ with L in [mm]
Average absolute error	23%
Cumulative error	0%
Standard deviation the error	29%
Lower confidence limit of 90%	-22%
Upper confidence limit of 90%	4%
Reference	Appendix F.2.5 page F-XX

Table 7.12 Properties of gouging time element

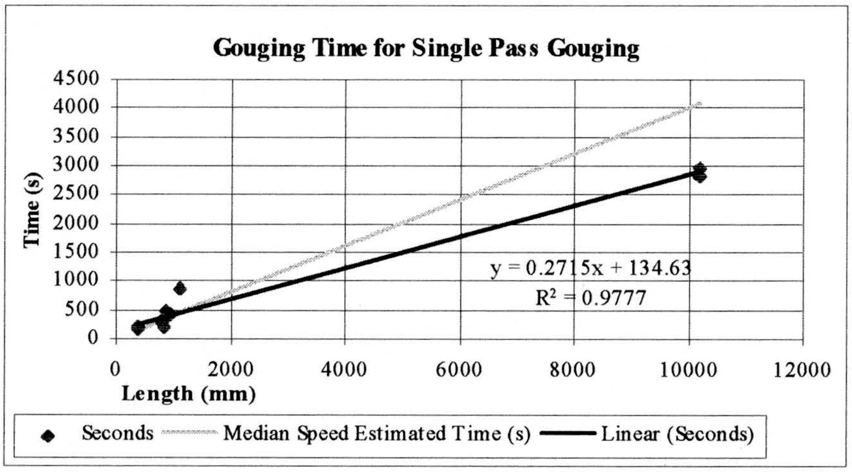

Figure 7.14 Gouging time vs. length

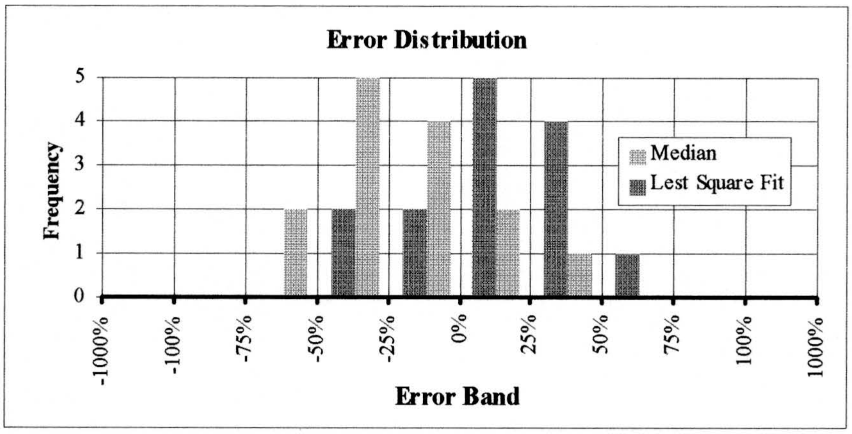

Figure 7.15 Error distribution for estimating gouging time

[6] Robust data analysis was not be used because the data set could not be divided into three representative groups.

Gouging rod usage = 2.249 mm gouged per mm of gouging rod. (for single pass).

Definition:

The distance that can be gouged with one unit length of gouging rod.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	20%
Cumulative error	14%
Standard deviation the error	23%
Lower confidence limit of 90%	-11%
Upper confidence limit of 90%	9%
Reference	Appendix F.2.6 page F-XXI

Table 7.13 Properties of gouging rod usage constant

The gouging rod usage was determined by taking the length gouged in one pass and dividing it by the actual length of the gouging rods used. The stub losses are excluded to make the model easily adaptable for gouging rod usage estimation if longer or shorter gouging rods are used. The median value was then determined for the recorded data points.

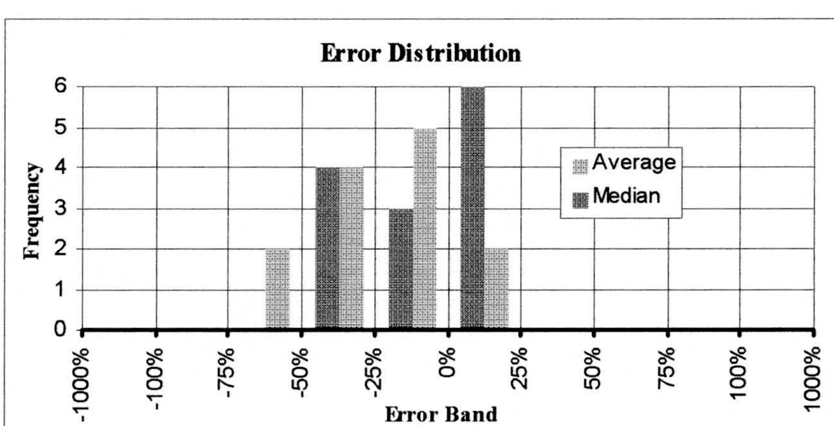

Figure 7.16 Error distribution for estimating the gouging rod usage

The gouging operators tended to use an average length of 227 mm of each 305 mm gouging rod. This resulted in a stub loss of 78 mm.

7.7.1.2. Procedure for Estimating the Gouging Time

The time formulas presented in Table 7.15 estimates the gouging time per weld section and a few additional gouging parameters. The formulas were constructed according to the process flow diagram, Figure 7.17. Table 7.14 summarises the occurrence of time elements for back gouging.

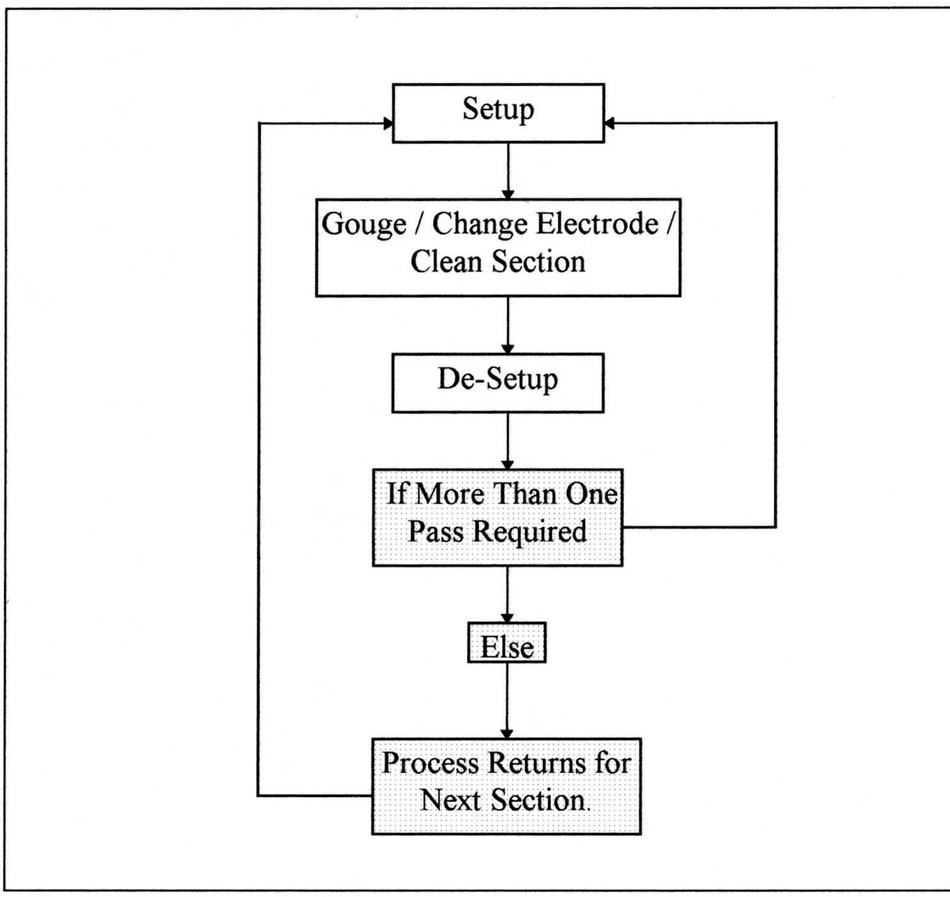

Figure 7.17 Process flow diagram for back gouging

Element Description	Occurrence
Gouging Set-up Time	Per weld section that requires gouging
Gouging De-set-up Time	Per weld section that requires gouging
Gouging Time	Per gouging pass

Table 7.14 Occurrence of back gouging time elements

Gouging Process Time			
Description	**Constant/Formula**	**Unit**	**Variable Declaration**
Gouging time	$67 + N \cdot (0.272 \cdot L + 135)$	s	N : Number of passes required to obtain required gouging depth L : Length of weld section to be back gouged [mm]
Additional Gouging Parameters			
Area Removed	$N \cdot 101.96$	mm^2	
Gouging Rods Required	$round\left(\frac{L \cdot N}{511}\right)$		Round to nearest integer

Table 7.15 Back gouging time estimation formulas

The user must add the extra area required, caused by gouging, to the minimum area required to fill the weld section, in order to obtain more accurate electrode estimation and hence welding labour time estimation.

7.7.2. ***Back Grinding Time Estimation***

Back grinding of gouged sections is required to remove excessive oxides from the gouged section and to make the internal surface of the weld section more uniform. It will also make die pen inspection possible. This requirement is also pinned down by the designer when he specifies full penetration welding in critical areas.

The data recorded for back grinding showed that the grinding speed is proportional to the depth at which grinding takes place, which is the same as the gouged depth.

The study included times for grinder set-up, de-set-up, grinding speed, grinding time per disk and grind/cool-down ratios. Grind/cool-down ratios are needed for prolonged grinding periods. This only occurred with back grinding because the grinder operator wedges the grinder in the groove which causes excessive pressure on the grinding disk, while the grinder is working at its maximum output. The study was done for electric grinders with a power output of 2500 Watt.

Optimally, the grinder would start grinding and would stop when the grinder needs to cool-down or when a new grinding disk has to be inserted. Back grinding is, however, physically demanding and the operator is subjected to high levels of noise, with the result that the worker stops every now and then for a little break. Therefore, an operator limit was defined, that is to say, the time that the operator grinds before he stops.

The time estimation model assumes the same grinding time per disk as for bevel cleaning and surface grinding. Changing of grinding disks occurred when the grinder was cooling down hence changing time can be omitted.

The time study showed that the total production time for back grinding can be broken down into the following time elements:

1. Set-Up Time.
2. De-Set-Up Time.
3. Grinding Time.
4. Grinder Cool Down Time.

7.7.2.1. Constants for the Back Grinding Time

The constants and terms that were determined from the time study are as follows :

Grind/Cool-Down Ratio = 1.035

Definition:

The time required for cooling of an electric grinder as a ratio of the grinding time required to prevent overheating of the grinder.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	65%
Cumulative error	-4%
Standard deviation the error	94%
Lower confidence limit of 90%	-59%
Upper confidence limit of 90%	59%
Reference	Appendix B.1.5.1 page B-IX

Table 7.16 Properties of grind/cool-down constant

The Grind/Cool-Down ratio is defined as the grinding time divided by the cool-down time. The Grind/Cool-down ratios were taken as the median of the recorded data.

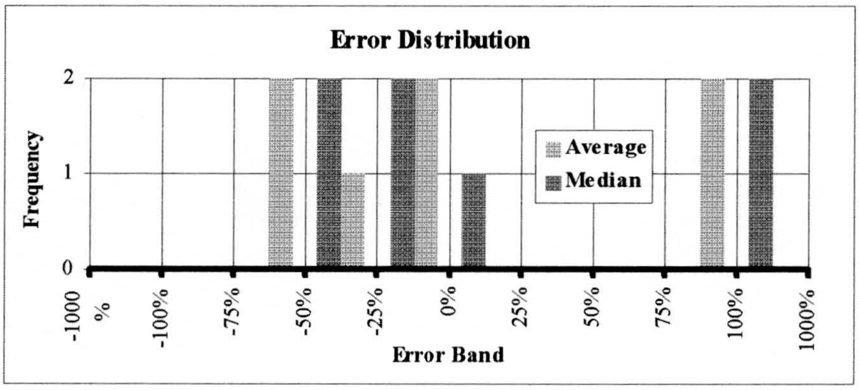

Figure 7.18 Error distribution for estimating the grind/cool-down ratio

The grind/cool-down ratio is a production related penalty that can be omitted if it can be assumed that there is enough grinders in the workshop to produce uninterrupted grinding time.

Back Grinding Speed $=915.56 \cdot D^{-0.7922}$ mm per minute

Definition:

The back grinding time is defined as the grinding length divided by the grinding speed at a specified grinding depth.

Statistical method used to obtain formula	Least square fit method on median values
Correlation coefficient	0.95
Valid range for formula	8≤D≤25 with D in [mm]
Average absolute error	14%
Cumulative error	-7%
Standard deviation the error	18%
Lower confidence limit of 90%	-7%
Upper confidence limit of 90%	9%
Reference	Appendix B.1.5.2 page B-X

Table 7.17 Properties of back grind time element

The grinding speed was determined with a power fit on the data after the median value for each group of depths have been determined.

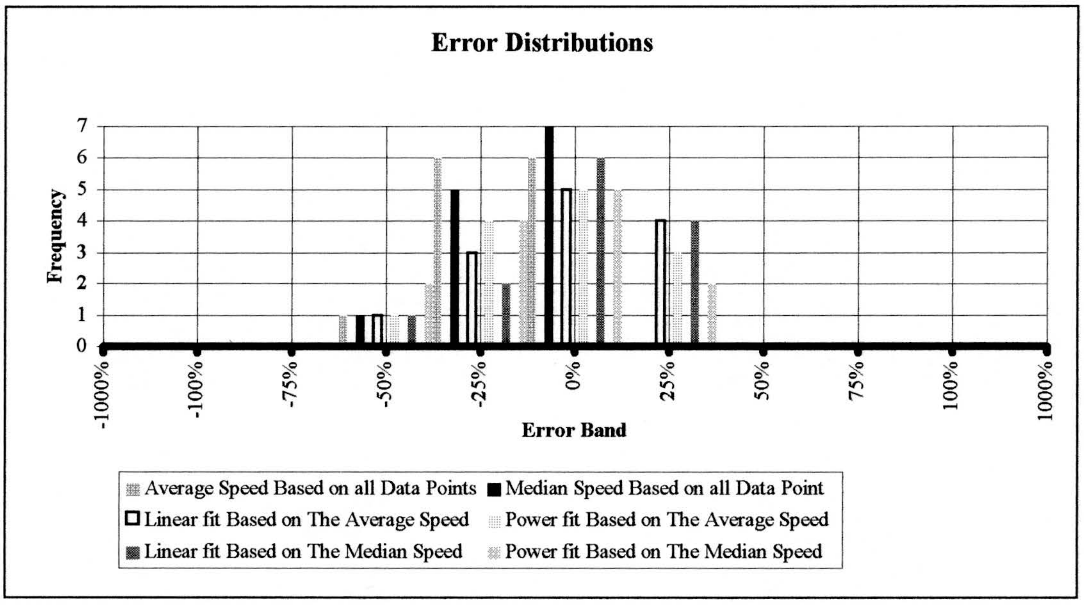

Figure 7.19 Error distribution for estimating the grinding time

Operator Limit = 364 seconds

Definition:

The average time that an operator can grind continuously before he needs a little break.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	49%
Cumulative error	-21%
Standard deviation the error	64%
Lower confidence limit of 90%	-19%
Upper confidence limit of 90%	19%
Reference	Appendix B.1.5.3 page B-XIV

Table 7.18 Properties of operator limit constant

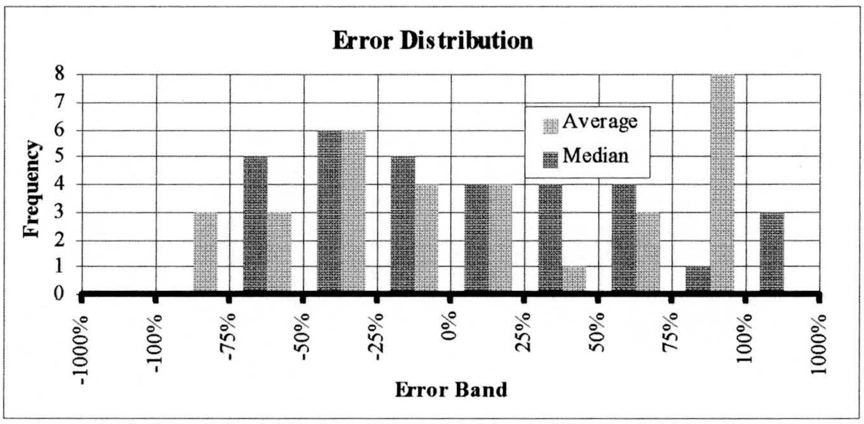

Figure 7.20 Error distribution for estimating the operator limit

The grinder set-up and de-set-up times are the same as the set-up times recorded for burr removal grinding.

7.7.2.2. <u>Time Estimation Procedure for Back Grinding</u>

The time formulas presented in Table 7.20 estimates the back grinding time per weld section. These formulas were constructed according to the process flow diagram, Figure 7.21. Table 7.19 summarises the time element occurrence for back grinding.

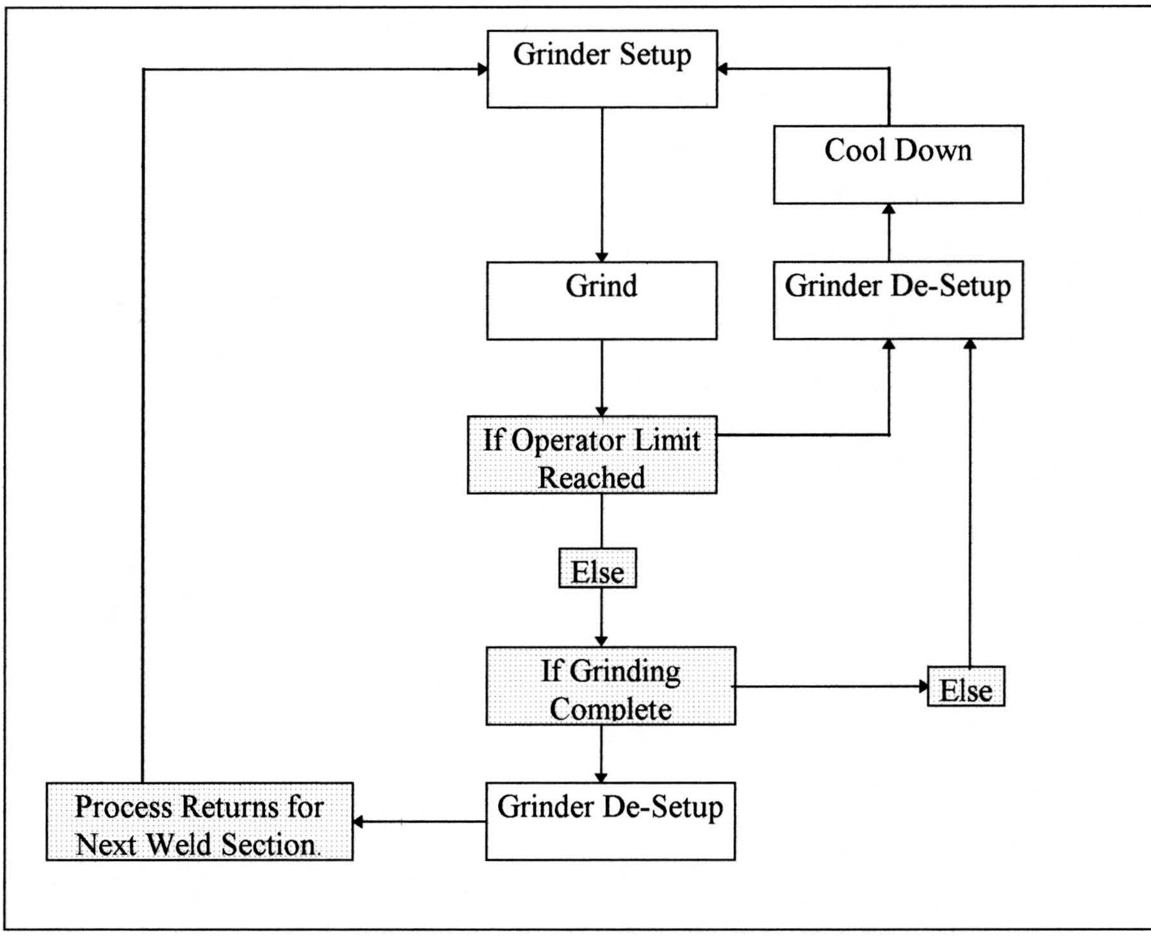

Figure 7.21 Process flow diagram for back grinding

Element Description	**Occurrence**
Grinding Time	Per weld section
Cool Down time	Proportional to grind time
Grinder Set-up Time	Per start stop sequence due to fatigue
Grinder De-set-up Time	Per start stop sequence due to fatigue

Table 7.19 Occurrence of back grinding time elements

Back Grinding Process Time			
Description	**Constant/Formula**	**Unit**	**Variable Declaration**
Back grinding time	$\frac{L}{915.56 \cdot D^{-0.7922}} \cdot 60$	s	L : Length of weld section to be back ground [mm] D : Depth to be back ground [mm]
StartStop	$round\left(\frac{T_{grind}}{364}\right)$		T_{grind} : Back grinding time Rounding is to the higher integer
Non grinding time	$\frac{L}{885 \cdot D^{-0.7922}} \cdot 60 + 52 \cdot StartStop$	s	

Table 7.20 Back grinding time estimation formulas

7.7.3. ***Surface Finishing Time Estimation***

Surface finishing of weld section surfaces are necessary to remove unwanted stress concentrations. These production times, and hence cost, are also pinned down by the designer the moment he specifies a weld section in a highly stressed region, especially in weld sections that have to withstand cyclic loads. The surface finish can vary from normal blend grinding to polishing. Polishing is normally done with a sanding disk after the surface of the weld has been blend ground. The sanding disk removes the grinding scratches caused by the grinding disk.

The time study has broken the total process of blend grinding and polishing down into the following time elements :

1. Grind Time (with abrasive disk)
2. Polish Time (with polishing disk)
3. Set-Up Time.
4. De-Set-Up Time
5. Operator limit (for blend grinding only).

7.7.3.1. Constants for Surface Grinding and Polishing Time

The constants and terms determined from the time study data are as follows :

The set-up and de-set-up times for surface grinding and polishing are the same as for other grinding operations.

Blend Grinding Speed = 3425 mm^2 per minute

Definition:

The blend grinding speed is defined as the area to be ground divided by the grinding speed.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	39%
Cumulative error	-16%
Standard deviation the error	55%
Lower confidence limit of 90%	-18%
Upper confidence limit of 90%	18%
Reference	Appendix B.1.6.1 page B-XVI

Table 7.21 Properties of blend grinding time element

The grinding speed was determined by taking the area of the weld section on the surface of the plate and dividing it by the recorded time. The median from the grinding speeds was then taken. Robust data analysis was also performed on the recorded data set but it produced a time estimation equation with a negative intercept on the time axis. This can cause a negative time estimation when the area is small.

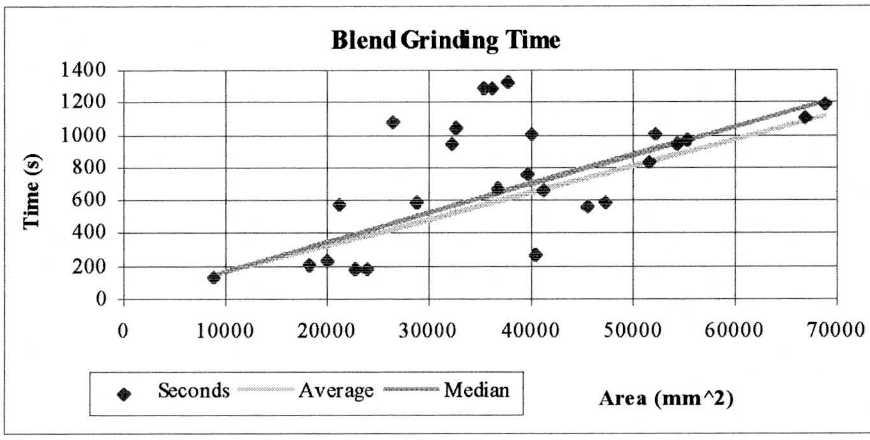

Figure 7.22 Blend grinding times vs. area

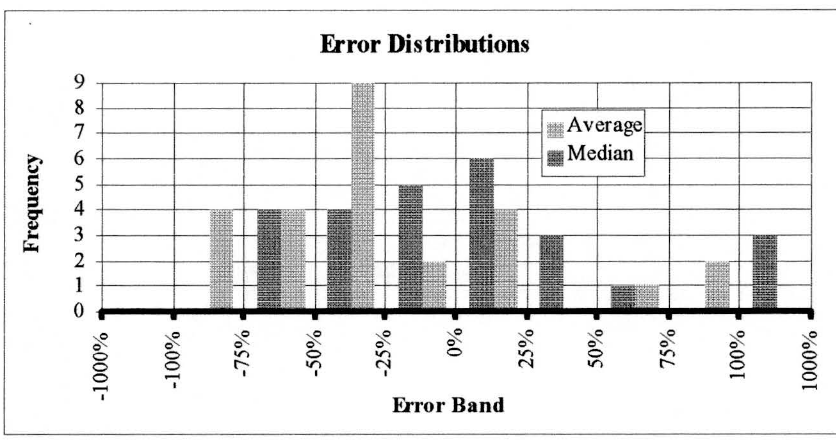

Figure 7.23 Error distribution for estimating the grinding time

Disk Time = 900 seconds

Statistical method used to obtain constant	Median of recorded data
Average absolute error	20%
Cumulative error	-0%
Standard deviation the error	23%
Lower confidence limit of 90%	-13%
Upper confidence limit of 90%	15%
Reference	Appendix B.1.4.3 page B-VII

Table 7.22 Properties of grinding time per disk

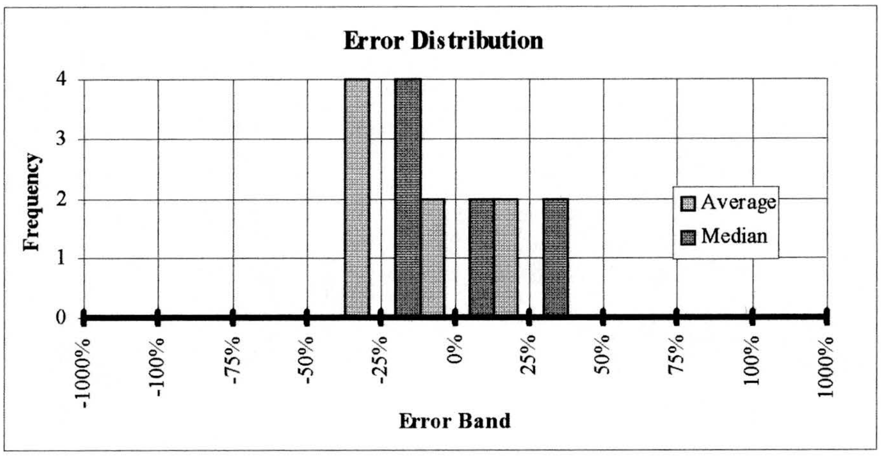

Figure 7.24 Error distribution foe estimating the grinding time per disk

Disk Change Time = 107 seconds

Statistical method used to obtain constant	Average of recorded data
Average absolute error	25.5%
Cumulative error	-8%
Standard deviation the error	33%
Lower confidence limit of 90%	-19%
Upper confidence limit of 90%	19%
Reference	Appendix B.1.4.4 page B-VIII

Table 7.23 Properties of disk change time element

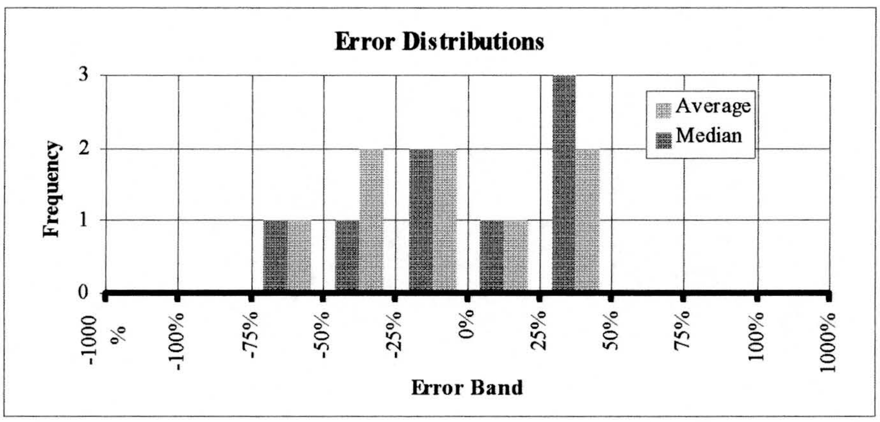

Figure 7.25 Error distribution for estimating the disk change time

Polish Speed = 14200 mm^2 per minute

Definition:

The polish time is defined as the area to be polished divided by the polish speed.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	23%
Cumulative error	-12%
Standard deviation the error	28%
Lower confidence limit of 90%	-13%
Upper confidence limit of 90%	13%
Reference	Appendix B.1.6.2 page B-XVII

Table 7.24 Properties of polish time element

The polish speed was determined by taking the area of the weld section on the surface of the material and dividing it by the recorded time. The median of these values were then taken as the polish speed.

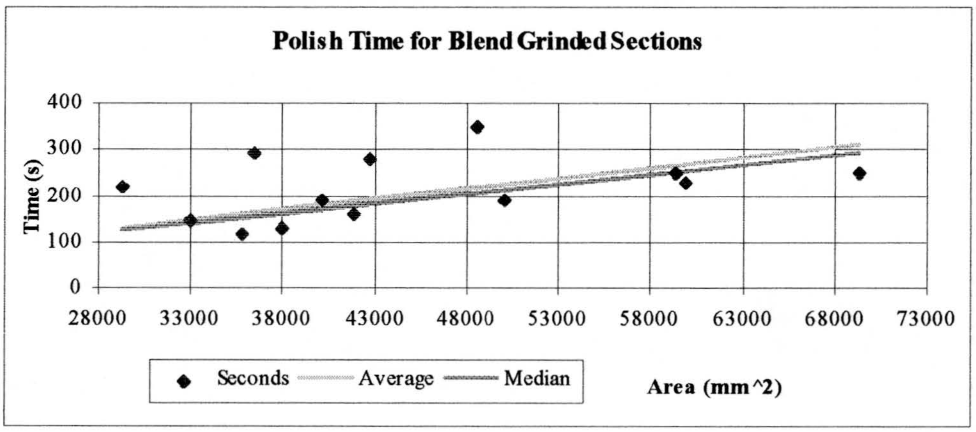

Figure 7.26 Polish time vs. area

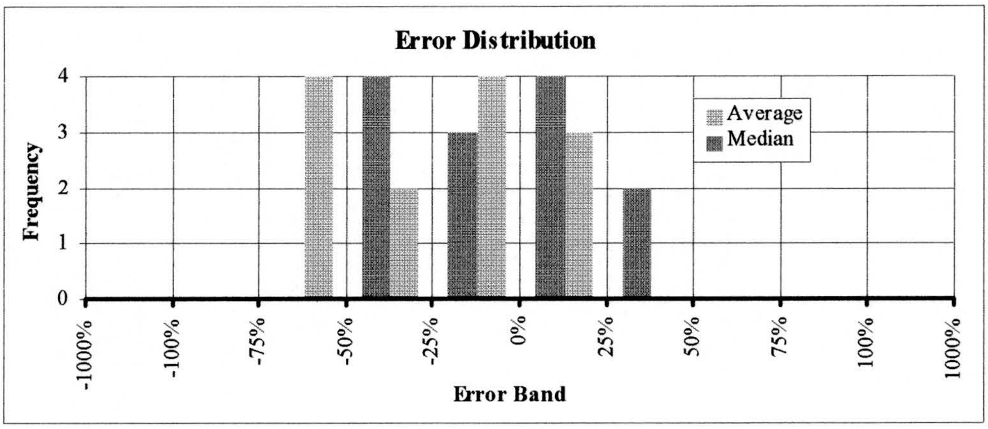

Figure 7.27 Error distribution for estimating the polishing time

7.7.3.2. Procedure for Estimating the Surface Grinding and Polish Time

The time formulas presented in Table 7.26 estimates the grinding and polishing time per weld section. The formulas were constructed according to the process flow diagram described in Figure 7.28. Table 7.25 summarises the time element occurrence for surface finish grinding.

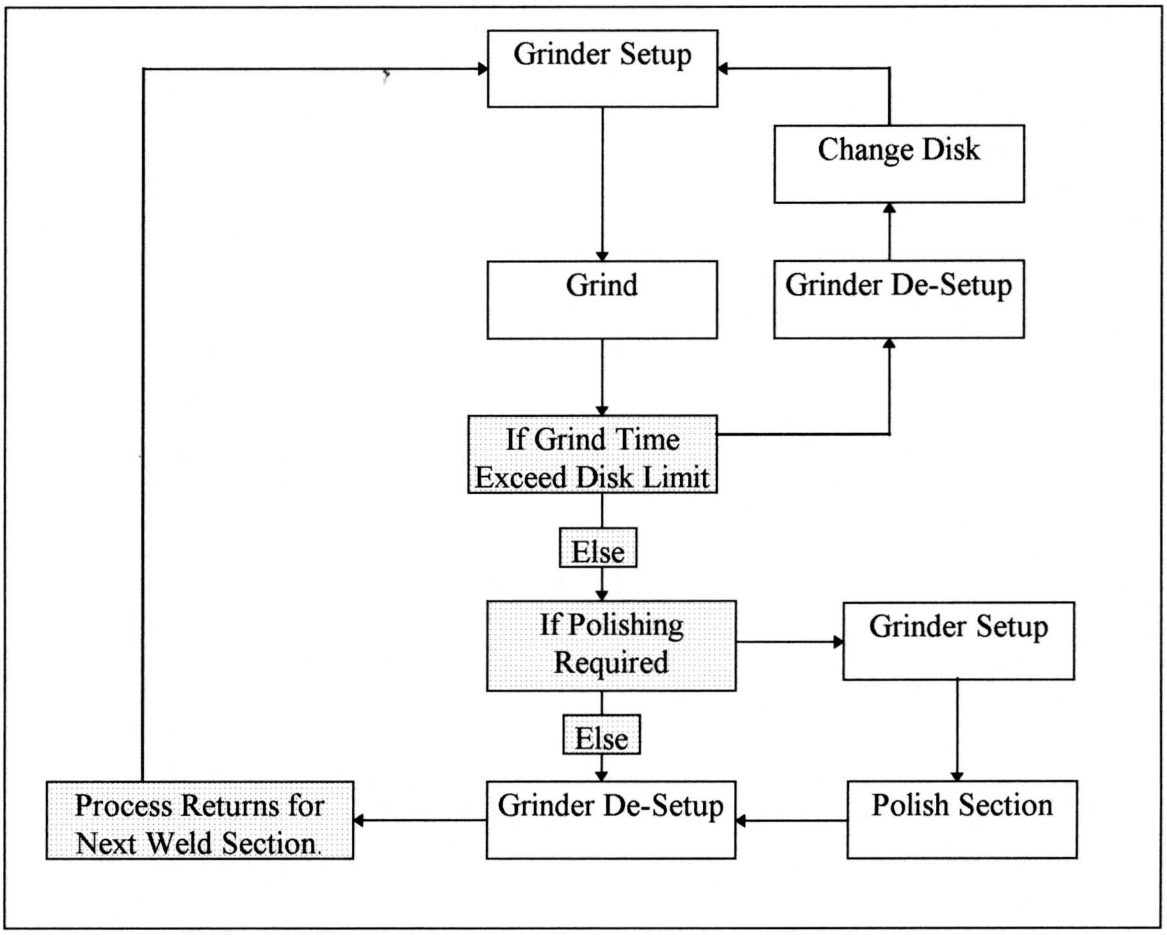

Figure 7.28 Process flow diagram for surface finish grinding

Element Description	Occurrence
Grinder Set-up Time	Per section and if grinding time exceeds allowed disk time
Grinder De-set-up Time	Per section and if grinding time exceeds allowed disk time
Disk Change Time	Per section if grinding time exceeds allowed disk time
Grind Time	Per section
Polish Time	Per section

Table 7.25 Occurrence of surface finishing time elements

Blend Grinding Process Times			
Description	**Formula**	**Unit**	**Variable Declaration**
Grind Time	$\frac{L \cdot W}{3425} \cdot 60$	s	L : Length of weld section to be surface finished [mm] W: Width of weld section on surface[mm]
Polish time	$\frac{L \cdot W}{14200} \cdot 60$	s	
Start Stop	$round\left(\frac{T_{Grind}}{900}\right)$		Round to higher integer T_{grind} : Surface grinding time
Non grinding time	$(30 + 22 + 107) \cdot StartStop$	s	
Non polishing time	30+22	s	

Table 7.26 Surface finishing time estimation formulas

7.8. Determining the Electrode Change Time

The electrode change time is considered for the assembly as a whole. For ease of use it is not included in the total welding time. The time needed to change the electrode will have an effect on the operating factor. It can, however, not be attributed to a specific weld section because, when the operator starts to weld one section with a new electrode pack and finishes it with say 10% left, then there will be electrode change time required for completion of the second weld section, which will affect the operating factor of the second weld section. The two weld sections will therefore not be comparable.

Electrode change time is defined as the total time needed to insert a new wire pack, from the time that the arc stops to the time when arc starts. Electrode change time is only a small part of the total welding time for assemblies welded with a continuous process. It will, however, be shown that the total electrode change time is directly proportional to the weight of electrode per pack available (i.e. purchase 15kg spools instead of 5kg spools).

7.8.1. ***Constants for Electrode Change Time***

The following electrode changing time was determined from the time study data :

Electrode Change Time = 685 seconds

Definition:

Total time taken by operator to remove empty wire spool, get new wire spool, fit new wire spool and draw electrode through welding nozzle.

Statistical method used to obtain constant	Median of recorded data
Average absolute error	7%
Cumulative error	-2%
Standard deviation the error	9%
Lower confidence limit of 90%	-6%
Upper confidence limit of 90%	6%
Reference	Appendix F.1.7 page F-XV

Table 7.27 Properties of electrode change time element

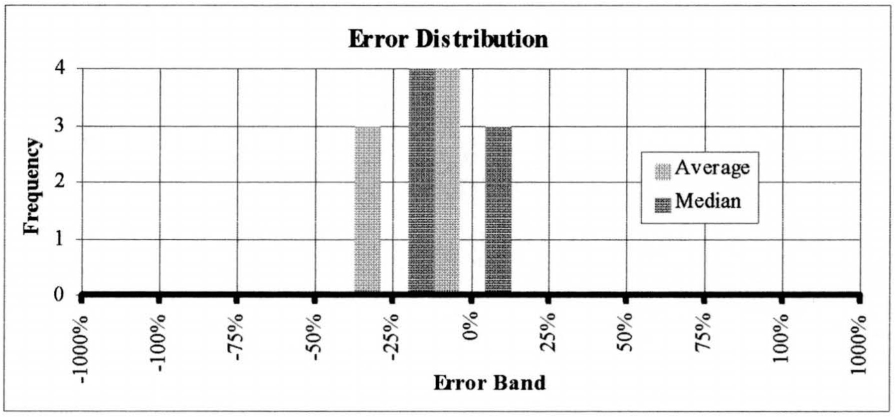

Figure 7.29 Error distribution for estimating the electrode change time

7.8.2. ***Procedure for Estimating Electrode Change Time***

The time formula presented in Table 7.28 estimates the electrode change time for an assembly.

Electrode Change Time			
Description	**Constant/Formula**	**Unit**	**Variable Declaration**
Total Electrode Change Time	$\frac{M_{electrode}}{M_{Pack}} \cdot 685$	s	$M_{electrode}$: Mass of electrode required to fill all weld sections [kg] M_{pack} : Mass of electrode per roll [kg]

Table 7.28 Electrode change time estimation formula

7.9. Power Cost

Power cost for welding is a small element of the total welding cost and can be included in the overhead cost. The power consumption of a weld section can be determined by calculating the power to produce the arc, and dividing it by the efficiency of the welding machine power supply [Cary, 1992]. The power consumption is directly proportional the voltage and current settings that the welding operator welds with and with which he feels comfortable.

7.10. Procedure for Estimating the Electric Energy

Power Consumption for Welding .

Definition of constants .

$Pidle := 375 \cdot watt$

The Power Consumed is Determined by :

$$P = \left[\frac{I \cdot V \cdot Tarc}{\eta} + (T - Tarc) \cdot Pidle \right] \cdot Joules$$

Where

I : Welding current (A)
V : Welding voltage (V)
η : Power plant efficiency
T : Total welding time (s)
Tarc : Arc time (s)

8. Model Verification

8.1. Tack Welding Time Estimation Verification

Two sub-assemblies of a large product were used to verify the answers of the tack welding time estimation model. The two sub-assemblies are shown in Figure 8.1 and Figure 8.2 respectively. The estimated times were compared to the hours booked by the operator on his time sheet. These booked times do not exclude time lost when the worker has a quick chat with the foreman, waiting for an overhead crane etc. and it is also somewhat suspect. It is therefore evident that the model should underestimate the booked times.

A Monte Carlo analysis was also performed for all the models presented within the theses. The analysis was done to show the effect of partial error cancellation of the underlying time elements. The analysis is however restricted to the scenario being analysed, because certain time elements (variable elements, e.g. bevelling cutting time) are dependent on part attributes. The occurrence of all time elements also affects the outcome of the Monte Carlo analysis. The occurrence of time elements is fixed by the part attributes and batch size.

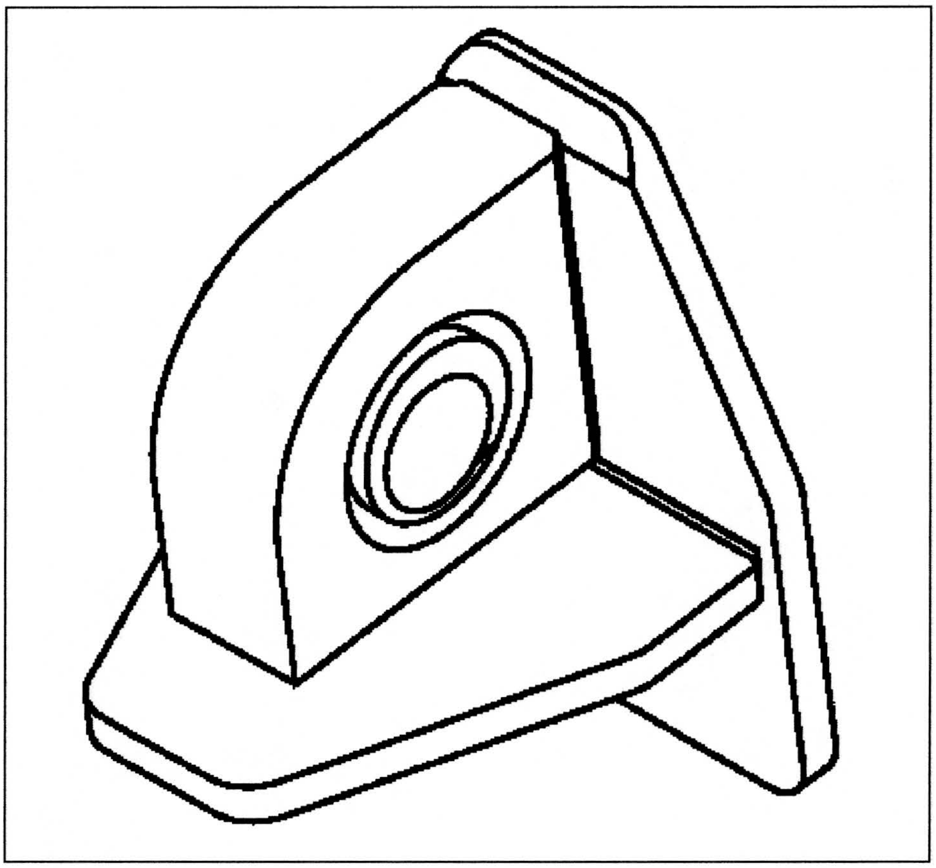

Figure 8.1 Sub-assembly-A

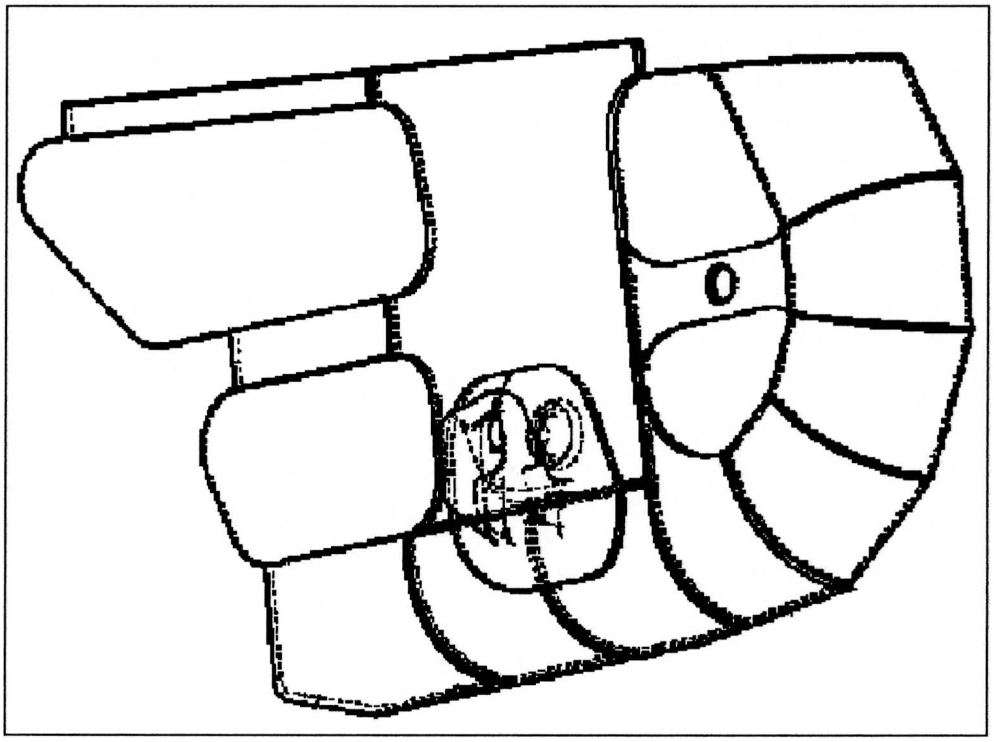

Figure 8.2 Sub-assembly-B

Assembly-A had a total part count of three different parts and was relatively small and simple to tack weld. It used approximately 1m^2 shop floor space and the storage area was ±30m from the tack welding area. All parts were obtained with an overhead crane and two operators were performing the tack welding task. Figure 8.3 shows the estimated time units and the booked time units for the making of the sub-assembly. The estimated times did not take operator efficiency into account. The upper and lower limits are also shown and are set at ±7% per part. Figure 8.4 shows the error distribution that can be expected for estimating the tack welding time of sub-assembly-A when using the model presented.

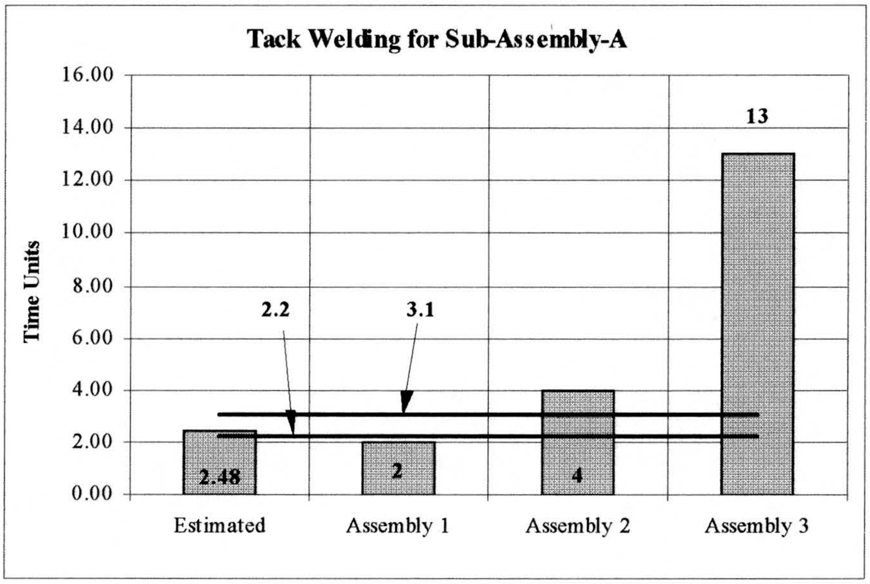

Figure 8.3 Estimated and booked times for sub-assembly-A

The normal time allowed for the assembly, which was estimated by the foreman, was ±2 time units. Assembly-3, therefore, clearly exceeded the allowed time units due to production related factors such as rework. The estimated times did not take operator efficiency into account.

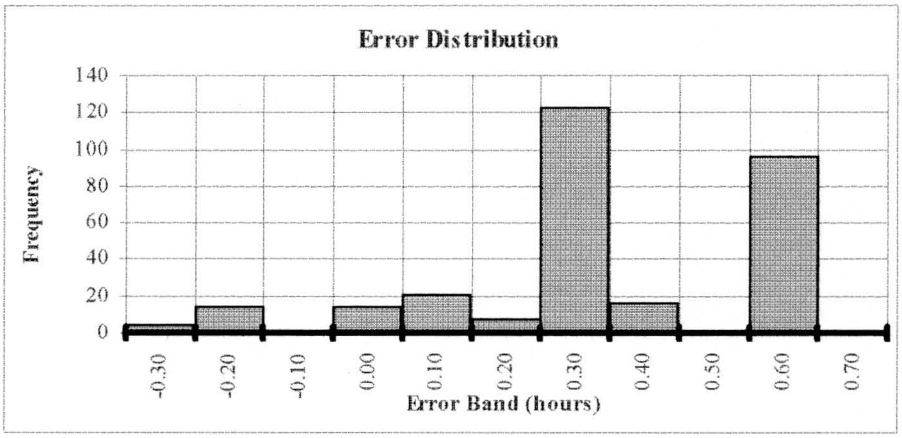

Figure 8.4 Error distribution obtained with Monte Carlo analysis

The wide scatter in the error distribution can be attributed to the low part count of the sub-assembly and further to one part that had greater dimensions and weight compared to the other parts. The distribution do, however, indicate that the model will probably under estimate the tack welding time for sub-assembly-A.

Assembly-B has a total part count of 16 with 14 different parts and was much larger than Assembly-A. Assembly-B contained seven curved parts which are more difficult to align than flat parts. It used $\pm 35m^2$ of floor space and was approximately 40m from the part storage area. Again, all parts were obtained with an overhead crane and two operators were performing the tack welding task. Figure 8.5 shows the estimated and booked times for the tack welding of Assembly-B. Figure 8.6 shows the error distribution that can be expected when estimating the tack welding time of sub-assembly-B.

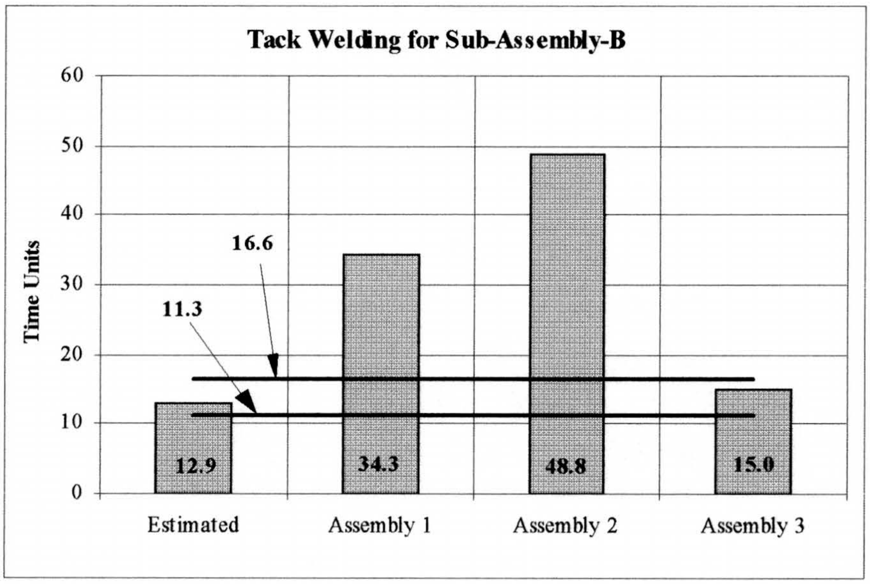

Figure 8.5 Estimated and booked times for sub-assembly-B

Recorded time study data for the tack welding of the Assembly-B showed that the side assembly can be built within one day by two operators. Assembly-1 and Assembly-2 exceeded the estimated tack welding time by more than 200% because of fit-up problems and low standard manufacturing of pre-formed parts. Assembly-1 and Assembly-2 also had rework done on them. Times were also booked for crack removal on the castings, something which is dependant on the quality of the casting.

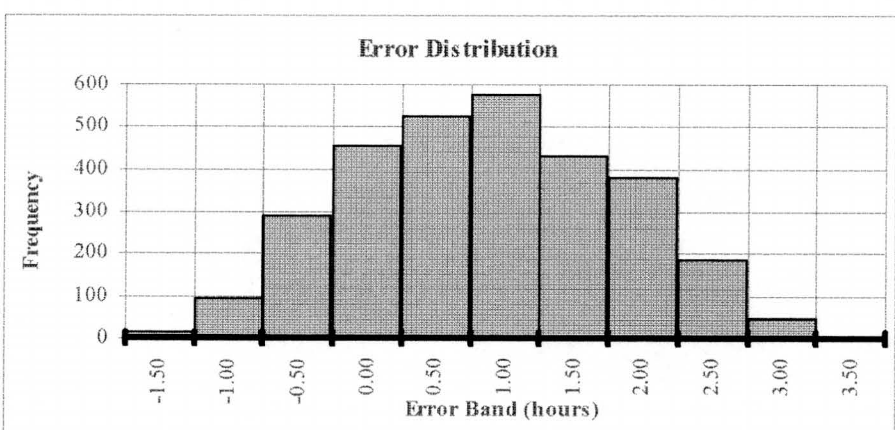

Figure 8.6 Error distribution obtained with Monte Carlo analysis

The error distribution follows a normal distribution quite well. This can be attributed to the larger part count for the sub-assembly and to the fact that the parts had similar attributes. The distribution do, however indicate that the model will tend to under estimate the tack welding time for sub-assembly-B.

8.2. Welding Time Estimation Verification

The two sub-assemblies described above were also used to verify the welding production time estimation model. The time estimated by the model was compared to the times booked by the welding operators. The model assumed an operating factor of 30% for both the assemblies. This coincides with average operating factors for heavy engineering obtained from the literature study. Figure 8.7 and Figure 8.9 shows the estimated and booked times for Assembly-A and Assembly-B respectively. The upper and lower limits for the estimation are also shown with a band error of ±11% which is caused by the accuracy with witch the welding current for the specified electrode can be estimated. Figure 8.8 illustrates the error distribution that can be expected for sub-assembly-A.

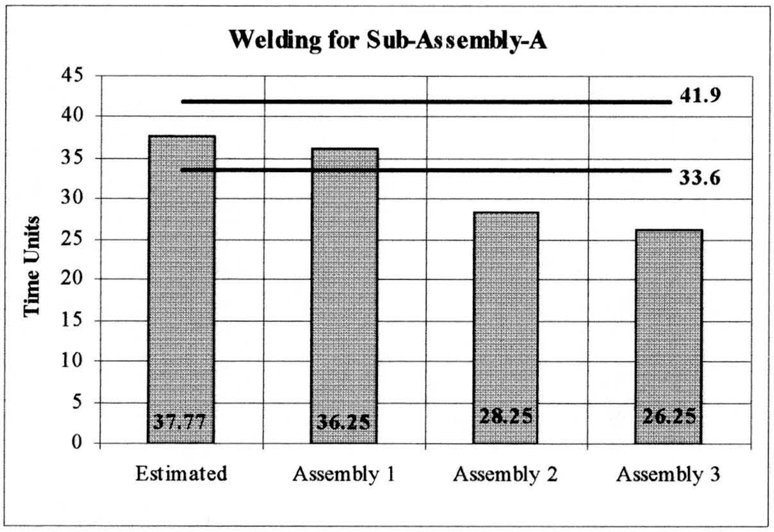

Figure 8.7 Estimated and booked welding times for sub-assembly-A

The model overestimated the welding time for Sub-Assembly-A. This can be attributed to the smaller size of the sub-assembly. The weld sections are more accessible which results in less worker movement. Therefore, a higher operating factor can be expected.

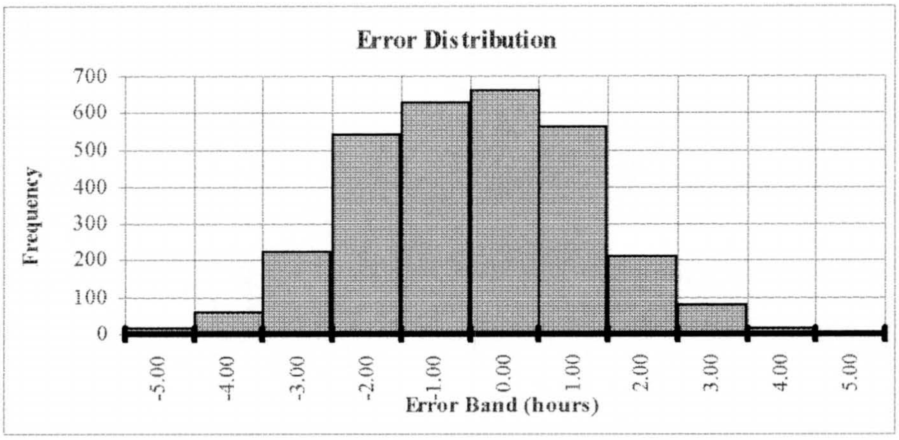

Figure 8.8 Error distribution obtained with Monte Carlo analysis

The error distribution shown for the time estimation of sub-assembly-A follows the normal distribution quite well. The smallest weld section had a volume of 161700 mm^3 while the largest weld section had a volume of 1050000 mm^3 (ratio of 6.5). All weld sections, therefore, had more or less the same influence on the total welding time estimation.

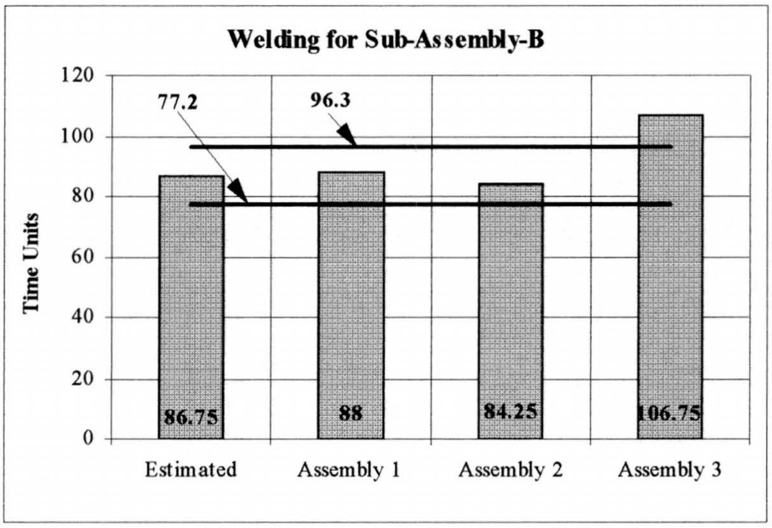

Figure 8.9 Estimated and booked times for sub-assembly-B

The estimated times for Sub-Assembly-B compared well with the booked times. The underestimation for Assembly-3 can be attributed to rework and crack removal.

Figure 8.10 shows the error distribution that can be expected for welding sub-assembly-B.

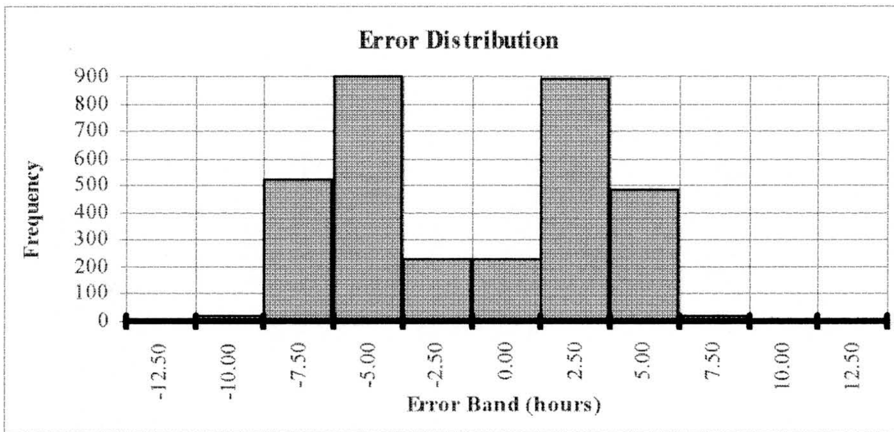

Figure 8.10 Error distribution obtained with Monte Carlo analysis

The double tops shown in the error distribution can be attributed to the variety of weld sections used for sub-assembly-B. The smallest weld section had a volume of 12224 mm^3 while the largest weld section had a volume of 4500000 mm^3, (ratio of 368). The larger weld sections, therefore, had a greater influence on the total weld time estimation. The double tops also indicates clearly that the main cost drivers for this assembly are the larger weld sections. The designer can, therefore, produce the greatest reduction for the welding time and cost of the assembly by looking at the design of the larger weld sections first. For this case it will be more likely to be 2.5 to 7 hours from the estimated time.

8.3. <u>Plate Bending Time Estimation Verification</u>

The time booked by the bending press operators were used to verify the time estimation of the model. This was done for the bending of 8 different parts and 16 parts in total. These parts included curved type bends and normal bends. Figure 8.11 shows the estimated and booked time units. The upper and lower limit is also given in Figure 8.11. The estimation does not take operator efficiency into account. Figure 8.12 shows the error distribution that can be expected when estimating the bending time.

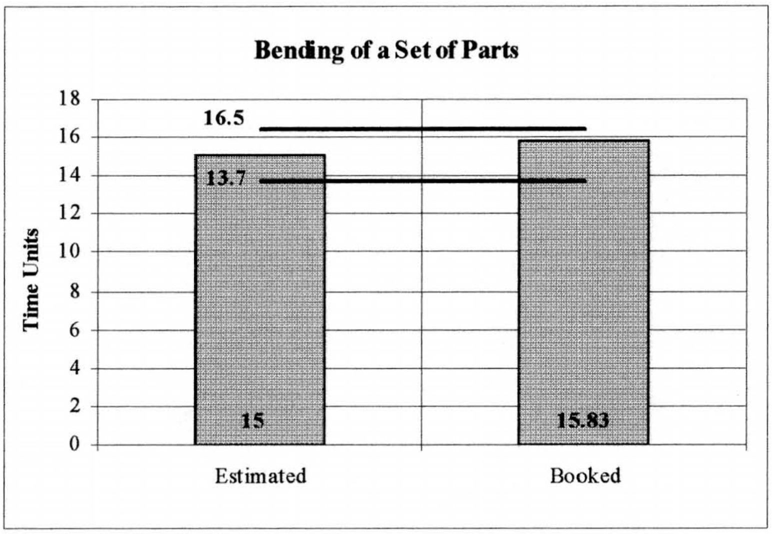

Figure 8.11 Estimated and booked bending time

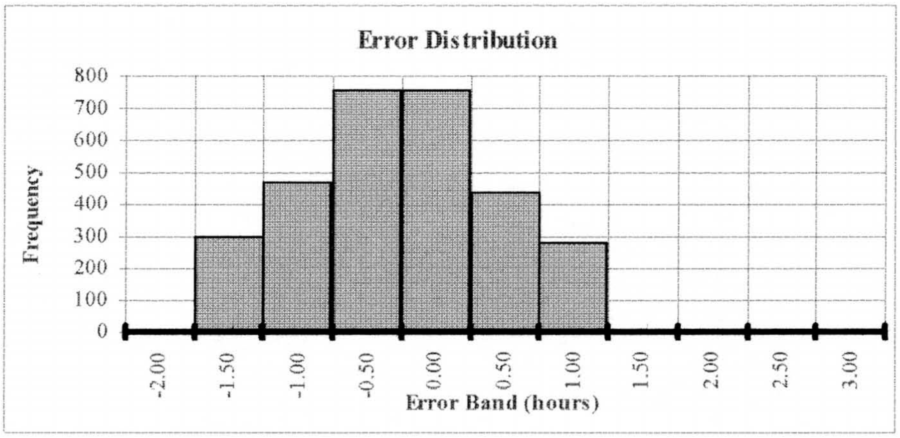

Figure 8.12 Error distribution obtained with Monte Carlo analysis

The error distribution follows the normal distribution quite well. Again, this can be attributed to the larger part count and to the bending of similar parts.

8.4. <u>CNC Flame Profiling and Bevelling Time Estimation Verification</u>

The CNC flame profile cutting time and the mechanised bevelling time of 5 similar parts were compared with the time estimated by the factory. An operator efficiency of 100% were used for both the models. The time units shown in Figure 8.13 includes the mechanised bevelling and CNC flame profile cutting time estimation. The upper and lower limit of the estimation is also given in Figure 8.13. The bevelling and profiling times were combined because the factory estimate came from one department. Figure 8.14 shows the error distribution that can be expected when estimating profiling and bevelling time.

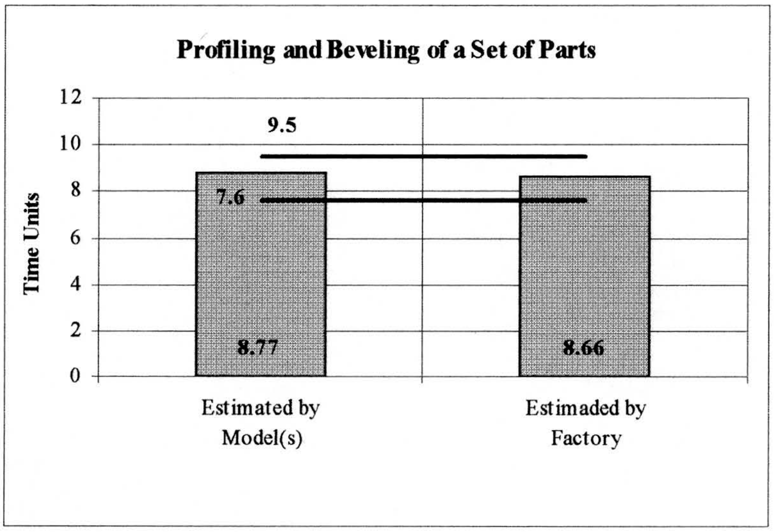

Figure 8.13 Model estimated and factory estimated time

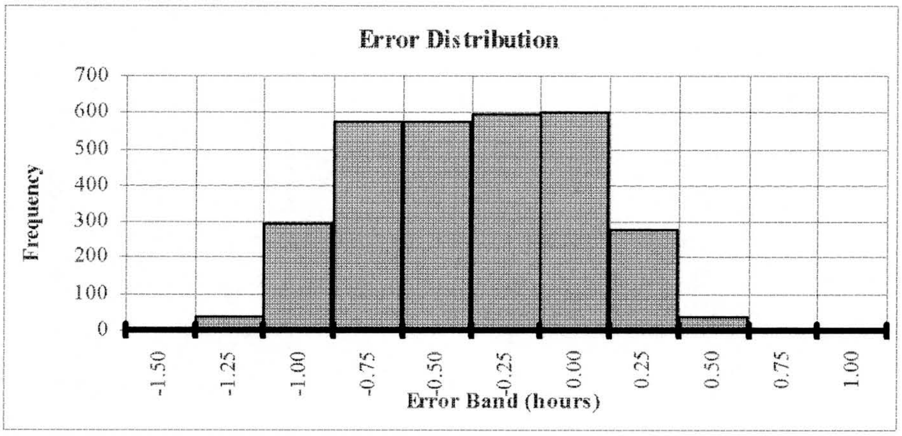

Figure 8.14 Error distribution obtained with Monte Carlo analysis

The error distribution follows the normal distribution quite well. Again, this can be attributed to a fairly large part count and the similarity of parts.

9. Conclusions

The following objectives were accomplished in the research field of fabricating large mechanical engineering assemblies:

1. The identification of the five main manufacturing processes needed to transform plate material into a final product. This also included the identification of secondary processes associated with each manufacturing process. These include:
   1.1. CNC flame profile cutting with burr removal grinding as a secondary process
   1.2. Manual and mechanised bevelling with clean grinding of the bevelled edge as a secondary process
   1.3. Plate bending
   1.4. Tack welding of an assembly
   1.5. Welding of an assembly with back gouging, back grinding and surface grinding as secondary processes
2. The identification of all operator or manufacturing tasks associated with each process and its secondary process (such as Set-up, cut, remove, trim etc.). Times were recorded for all these tasks.
3. Correlation's were investigated between design parameters and the recorded times for each time element.
4. The time elements were combined according to the process flow diagrams in order to obtain formulas. These formulas use inputs which are available to the designer to estimate the manufacturing time. Average settings were taken from the shop floor for inputs that are not readily available to the designer. This was done for all five manufacturing processes and their secondary processes.
5. The times estimated with these cost models were then compared to times booked by workers on their time sheets, where available. The CNC flame

profile cutting model and the Bevelling model were compared to the times estimated by the factory. The estimated times compared fairly well as can be seen in the previous chapter.

The minimum and maximum errors that can be expected, with a confidence of 90%, of the five cost models developed within this thesis are summarised in Table 9.1[7]

Model	**Minimum % Deviation**	**Maximum % Deviation**
CNC Flame Profile Cutting and Bevelling	-15%	9%
Bending	-9%	10%
Tack Welding	-11%	17%
Welding	-11%	11%

Table 9.1 Summary of minimum and maximum errors

The cost models developed here will, therefore, give the designer the ability to check manufacturing times and cost for an initial design and redesign. This will allow trade-off studies between different design alternatives with manufacturing time and cost as decision making parameters.

It is the authors opinion that the objectives were met in establishing the direct labour cost which can be combined with material and consumable costs to get a more representative estimate of the direct manufacturing cost. Material costs can be obtained from the bill of materials and suppliers.

Table 9.2 summarises the advantages and disadvantages for each cost model presented within this thesis.

[7] Note that the error bands are dependant on the weight that each time element has on the total time estimated. The figures presented here will, therefore, deviate slightly with different design variables.

Advantages	Shortcomings
CNC Flame Profile Cutting	
1. Estimates the profiling time 2. Estimates grinding time	1. Does not include LP-gas and Oxygen consumption
Manual and Mechanised Bevelling	
1. Estimates bevelling time 2. Estimates additional time required for grinding operations	1. Does not include LP-gas and Oqygen consumption
Plate Bending	
1. Estimates the bending time for normal, channel (with or without back set) and curved bends	1. Does not include gas consumable which may be required for heating harder plates so that they can be bent.
Tack Welding	
1. Estimates the tack welding time of an assembly 2. Estimates the trimming that may be required	1. Does not include gas consumable used for preheating. 2. Does not include welding consumable used for tack welding.
Welding	
1. Estimates the welding time and consumable required 2. Includes time estimation for secondary processes (such as back grinding, back gouging, surface grinding and surface polishing). 3. Estimate the preheating time 4. Estimate material lost due to back gouging so that it can be included in the welding time and consumable requirements	1. Does not differentiate between overhead, down-hand and vertical welding

Table 9.2 Advantages and shortcomings of models

The estimation models will also indicate areas of long production time and hence high cost in the design. This will allow optimisation of the design that are aimed at reducing the cost and/or production time. See Appendix G for a simple "Design Example" that illustrates the use of the models.

10. Further Work

Future development can optimise the use of the models by relating the input parameters of one process to the input parameters of another process. This has been done for the time estimation of secondary processes.

The direct manufacturing time estimation models can also include more manufacturing processes other than the five processes included within this thesis, such as:

1. Machining of components
2. Plate rolling as an alternative to plate bending
3. Drilling of large diameter holes in plate material as an alternative to CNC profiling of holes which are machined afterwards for the fitting of bushes.
4. The model can further also include different welding processes related to the fabrication of large engineering products such as:
   - 1.1.1. Mechanised welding methods
   - 1.1.2. Electroslag welding
   - 1.1.3. Submerged arc welding process

So that a trade-off study can be done, with cost and time as decision making parameters, between different manufacturing processes and design alternatives.

11. References

- Afrox, 1996, Product Catalogue, South Africa, Germiston (Cent.Wits) tel. (011) 873-4310.
- Alloy Rods, 1994, Product Catalogue.
- Amstead, B.H., Ostwald, P.F., Begeman, M.L., 1987, Manufacturing Processes, Eighth Edition, John Wiley & Sons, Inc., USA
- Barnes, R.M., 1980, Motion and Time Study, Design and Measurement of Work, Seventh Edition, John Wiley & Sons. Inc. New york
- Blanchard, B.J. and Fabrycky, W.J., 1990, Systems Engineering and Analysis, Second Edition, Prentice Hall.
- Boothroyd, G., Dewhurst P. and Knight, W., 1994, Product Design for Manufacture and Assembly, Marcell Dekker, Inc., New York
- Cary, J., 1992, Modern Welding Technology, Prentice Hall.
- Farkas, J. and Jarmai, K., 1995, "Fabrication cost calculations and minimum cost design of welded structural parts", Welding in the world, Vol. 35. No. 6, pp. 400-406.
- Feder, D.K.,1993, "Cost implications in the design of welded steel structures", Welding in the World, Vol. 31, No. 4, pp. 13-20.
- Harnisfeger (P&H), 1998, Corporate Standard.
- Helander, M.G., 1994, "Cognitive and Sociotechnical Issues in Design for Manufacturability", The International Journal of Human Factors in Manufacturing, Vol. 4, pp. 375-390.
- Hundal, M.S., 1993, "Rules and Models for Low-Cost Design", Design for Manufacturability, ASME, DE-Vol. 52, pp. 75-84.
- Hundal, M.S., 1995, "Time and Cost Driven Design", Design for Manufacturing, ASME, DE-Vol. 81, pp. 9-20.
- Hoaglan, D.C., Mosteller, F. and Tukey, J.W., 1982, Understanding Robust and Exploratory Data Analysis, John Wiley & Sons, Inc. New York
- Keubler, P., "Cost Effective Selection and Utilisation of Welding Processes", Commonwealth Gasses Limited. International Conference of South African

Welding Institute, CSIR Conference Centre, 12-14 March 1991.

- Lincoln Electric, 1994, The Procedure Handbook of Arc Welding, The Lincoln Electric Company, Ohio
- Logan, H., 1991, "Cost associated with plate preparation by flame cutting", National sales manager, Messer Griesheim Australia, International Conference of South African Welding Institute, CSIR Conference Centre, 12-14 March 1991.
- Miles, B.L., 1989, "Design for assembly—a key element within design for manufacture", Journal of Automobile Engineering., Vol. 203, pp. 29-36.
- Mills, A.F., 1992, Heat Transfer, International Student Edition, Irwin.
- Nichols, K., "Better Cheaper Faster Products by Design", Journal of Engineering Design, Vol. 3. No. 3. 1992, pp. 217-227.
- Niebel, B.W., 1988, Motion and Time Study, Eighth Edition, Richard D. Erwin, USA
- O'Connor, P.D.T., 1991, Practical Reliability Engineering, Third Edition, John Wiley & Sons Inc. Chichester
- Phelps, M., November 1990, "Welding Economics", Welding and Metal Fabrication, Basic Welding Data. No. 19, pp. 508-512.
- Reynolds, D.E.H., 1991, "Productivity with Quality - A Return to Basics", President, Canadian Welding Bureau, Canada. International Conference of South African Welding Institute, CSIR Conference Centre, 12-14 March 1991.
- Salter, G.R.,1979, "An Economic View of Arc Welding", Head of Arc Welding, The Welding Institute, Cambridge , England.
- Sim, P. A., Fire Fighting Enterprise, Australia Limited, "Estimating for time labour and overhead costs for welded structures", International Conference of South African Welding Institute, CSIR Conference Centre, 12-14 March 1991.
- Speedarc Guidelines, 1997, "Products for welding ...'Automatically'", Wasa Electrodes South Africa. 108 Main Reef Road Technicon, Roodepoort , South Africa.
- Wasa Product Catalogue, 1997, "Products for welding ...'Automatically'", Wasa Electrodes South Africa. 108 Main Reef Road Technicon, Roodepoort , South Africa.

Appendices

Appendix-A

CNC Flame Profile Cutting Data

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A.1. **Constants for CNC Flame Profile Cutting**

A.1.1. **Set-up Time for CNC Flame Profiling**

Set-up time for the CNC profiling machine = 600 seconds. The set-up time was taken as the median value of the recorded data, this value gave the smallest errors.

					Based on the Total Machine Set-up Time			
n	Recorded Time	No. Flames	Seconds	Set-up Time per Flame (s)	Average (s)	Median (s)	Error of Average	Error of Median
1	09:51.0	3	591	197	613.72	600	4%	1.52%
2	12:15.0	4	735	183.75	613.72	600	-16%	-18.37%
3	03:54.0	-	234	-	613.72	600	162%	156.41%
4	06:08.0	-	368	-	613.72	600	67%	63.04%
5	06:07.0	-	367	-	613.72	600	67%	63.49%
6	12:40.0	-	760	-	613.72	600	-19%	-21.05%
7	11:43.0	2	703	351.5	613.72	600	-13%	-14.65%
8	13:56.0	2	836	418	613.72	600	-27%	-28.23%
9	16:12.0	2	972	486	613.72	600	-37%	-38.27%
10	09:45.0	1	585	585	613.72	600	5%	2.56%
11	10:00.0	1	600	600	613.72	600	2%	0.00%
						Average Absolute Error	38.11%	37.05%
						Cumulative Error	0.00%	-2.24%
						Standard Deviation	58.95%	57.63%
						Median of Error	2.29%	0.00%
						Confidence		
						90%	29.24%	28.58%

Table 1.1 Data for CNC Flame Profile Cutting Machine Set-up

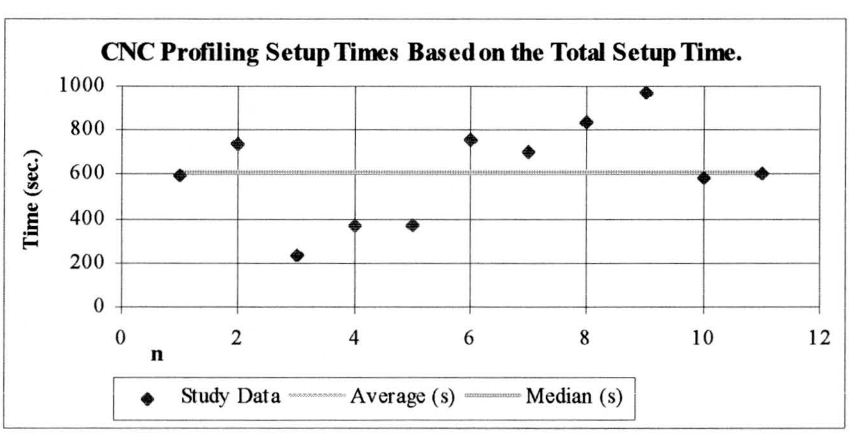

Figure 1.1 Data Plot for Set-up Time

It was decided not to use the set-up time per flame because this is something that the designer is not likely to know and the errors given when using the set-up time per flame is bigger than that given by the set-up time based on the total set-up time.

A.1.2. Machine De-Set-up Time for CNC Profiling

De-Set-up time for the CNC profiling machine = 88 seconds. The machine set-up time was determined by taking the median of the recorded data. The median value gave the smallest errors when used to estimate the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	01:28.0	88	179	88	103%	0%
2	01:08.0	68	179	88	163%	29%
3	06:10.0	370	179	88	-52%	-76%
4	04:20.0	260	179	88	-31%	-66%
5	01:14.0	74	179	88	142%	19%
6	05:32.0	332	179	88	-46%	-73%
7	01:01.0	61	179	88	193%	44%
				Average Absolute Error	104.41%	44.07%
				Cumulative Error	0.00%	-50.84%
				Standard Deviation	106.98%	52.60%
				Median of Error	103.41%	0.00%
				Confidence		
				90%	66.51%	32.70%

Table 1.2 Data for CNC Flame Cutting Machine De-Set-up

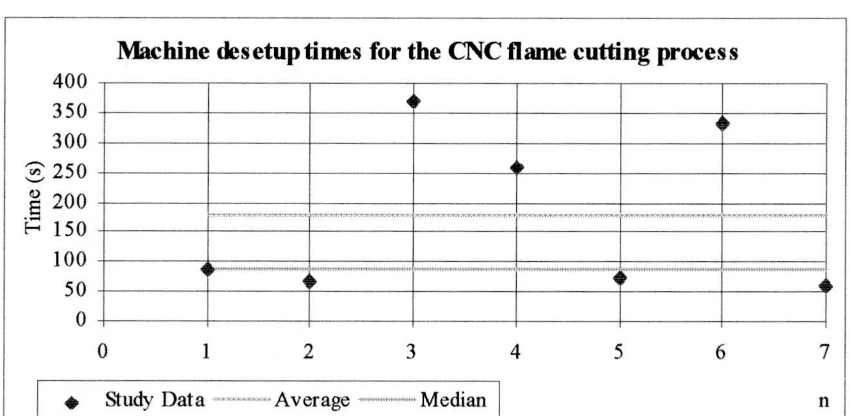

Figure 1.2 Data Plot for De-Set-up Time

A.1.3. Cutting Speed for CNC Profiling with LP-Gas

The cutting speed for the CNC profiling process was determined by taking the median and average values of the cutting speeds of the recorded data of a specific plate thickness. Linear, logarithmic and power law curve fits were then constructed with the least squares method on these median and average values. The fit which produced the smallest errors for the recorded data was the power fit on the median values. This equation is valid for a plate thickness range 8 mm to 200 mm.

n	Recorded Time	Length mm	Thickness mm	Time s	Speed mm/min	Average values mm/min	Median Values mm/min	Factory Specified Speed[1] mm/min	Afrox Speed mm/min [Afrox, 1994]
1	02:15.0	850	8	135	377.77	320.33	320.33	450	323.25
2	03:14.0	850	8	194	262.88				
3	02:24.0	830	10	144	345.83	336.35	345.83	400	321
4	02:30.0	830	10	150	332				
5	02:24.0	830	10	144	345.83				
6	02:22.0	830	10	142	350.70				
7	02:42.0	830	10	162	307.40				
8	04:03.0	1300	16	243	320.98	302.00	297.20	350	315.4
9	01:32.0	455.71	16	92	297.20				
10	01:35.0	455.71	16	95	287.81				
11	02:50.0	800	25	170	282.35	271.89	267.85	300	311
12	01:52.0	500	25	112	267.85				
13	01:53.0	500	25	113	265.48				
14	03:38.0	1032	30	218	284.03	284.03	284.03	300	301.66
15	06:53.0	1182.9	50	413	171.84	191.95	173.52	250	282.03
16	02:28.0	534.29	50	148	216.60				
17	06:49.0	1182.9	50	409	173.52				
18	02:30.0	534.29	50	150	213.71				
19	06:51.0	1182.9	50	411	172.67				
20	06:51.0	1182.9	50	411	172.67				
21	02:24.0	534.29	50	144	222.61				
22	05:41.0	597.14	55	341	105.06	105.27	105.37	250	277.12
23	05:40.0	597.14	55	340	105.37				
24	05:40.0	597.14	55	340	105.37				
25	04:42.0	502.86	70	282	106.99	106.99	106.99	250	262.40
26	04:41.0	502.86	70	281	107.37				
27	04:43.0	502.86	70	283	106.61				
28	15:24.0	2065.4	125	924	134.11	134.04	134.04	250	208.43
29	15:25.0	2065.4	125	925	133.96				
30	15:25.0	2065.4	125	925	133.96				
31	15:24.0	2065.4	125	924	134.11				
32	18:00.0	1620	200	1080	90	82.86	83.86	250	134.83
33	09:22.0	700	200	562	74.73				
34	11:34.0	970	200	694	83.86				

Table 1.3 Recorded Cutting Speed Data and Suggested Speeds by Factory and Affrox for Various Plate Thicknesses

[1] Suggested cutting speeds for profiling time estimation by Factory

Plate Thickness	Average Values	Median Values	Factory Speed mm/min	Afrox Speed mm/min
8	320.33	320.33	450	323.25
10	336.36	345.83	400	321
25	271.9	267.85	300	311
30	284.04	284.03	300	301.66
50	191.95	173.52	250	282.035
55	105.28	105.37	250	277.128
70	106.99	106.99	250	262.409
125	134.04	134.04	250	208.437
200	82.865	83.86	250	134.838

Table 1.4 Summary of Average, Median, Factory and Afrox Cutting Speeds vs. Material Thickness

	Error of Linear fit on Average Values	Error of Logarithmic fit on Average values	Error of Power fit on Average Values	Error of Linear fit on Median Values	Error of Logarithmic fit on Median values	Error of Power fit on Median Values
Average Absolute Error	31.84%	20.38%	17.87%	31.90%	20.68%	17.96%
Cumulative Error	0%	-1%	-3%	-1%	-1%	-4%
Standard Deviation	46%	28%	23%	45%	28%	23%
Median of Error	-6%	-7%	-5%	-6%	-7%	-5%
Confidence						
90%	13%	8%	7%	13%	8%	6%

Table 1.5 Summary of Errors Produced by Different Functions Fitted

n	Error of Linear Fit on Average Values	Error of Logarithmic Fit on Average Values	Error of Power Fit on Average Values	Error of Linear Fit on Median Values	Error of Logarithmic Fit on Median Values	Error of Power Fit on Median Values
1	-27.54%	-9.17%	-0.67%	-27.91%	-8.88%	-0.92%
2	4.13%	30.53%	42.74%	3.60%	30.94%	42.39%
3	-21.58%	-6.33%	-1.92%	-21.97%	-6.11%	-2.25%
4	-18.31%	-2.43%	2.16%	-18.72%	-2.20%	1.83%
5	-21.58%	-6.33%	-1.92%	-21.97%	-6.11%	-2.25%
6	-22.66%	-7.63%	-3.29%	-23.06%	-7.42%	-3.60%
7	-11.77%	5.38%	10.34%	-12.22%	5.62%	9.97%
8	-17.86%	-11.68%	-14.59%	-18.28%	-11.66%	-15.02%
9	-11.28%	-4.61%	-7.75%	-11.74%	-4.59%	-8.22%
10	-8.39%	-1.50%	-4.74%	-8.87%	-1.48%	-5.22%
11	-10.62%	-13.19%	-20.67%	-11.11%	-13.41%	-21.20%
12	-5.79%	-8.49%	-16.37%	-6.29%	-8.72%	-16.93%
13	-4.94%	-7.67%	-15.63%	-5.46%	-7.90%	-16.19%
14	-13.37%	-19.23%	-27.39%	-13.84%	-19.54%	-27.92%
15	28.56%	7.94%	-4.76%	27.79%	6.98%	-5.64%
16	2.00%	-14.37%	-24.44%	1.38%	-15.12%	-25.14%

17	27.32%	6.89%	-5.69%	26.55%	5.95%	-6.55%
18	3.38%	-13.21%	-23.42%	2.75%	-13.98%	-24.13%
19	27.94%	7.41%	-5.22%	27.17%	6.46%	-6.10%
20	27.94%	7.41%	-5.22%	27.17%	6.46%	-6.10%
21	-0.76%	-16.68%	-26.48%	-1.36%	-17.42%	-27.16%
22	104.29%	68.73%	49.18%	103.02%	67.04%	47.76%
23	103.69%	68.23%	48.75%	102.43%	66.55%	47.33%
24	103.69%	68.23%	48.75%	102.43%	66.55%	47.33%
25	82.99%	46.31%	31.35%	81.77%	44.31%	29.98%
26	82.34%	45.79%	30.88%	81.12%	43.80%	29.52%
27	83.64%	46.82%	31.81%	82.41%	44.82%	30.44%
28	-5.57%	-20.48%	-19.41%	-6.51%	-22.71%	-20.42%
29	-5.47%	-20.39%	-19.32%	-6.41%	-22.63%	-20.34%
30	-5.47%	-20.39%	-19.32%	-6.41%	-22.63%	-20.34%
31	-5.57%	-20.48%	-19.41%	-6.51%	-22.71%	-20.42%
32	-64.06%	-26.43%	-2.93%	-65.36%	-30.53%	-4.32%
33	-56.71%	-11.40%	16.90%	-58.28%	-16.34%	15.23%
34	-61.42%	-21.04%	4.18%	-62.82%	-25.45%	2.69%

Table 1.6 Detailed Errors of Different Fits for Each Data Point Recorded

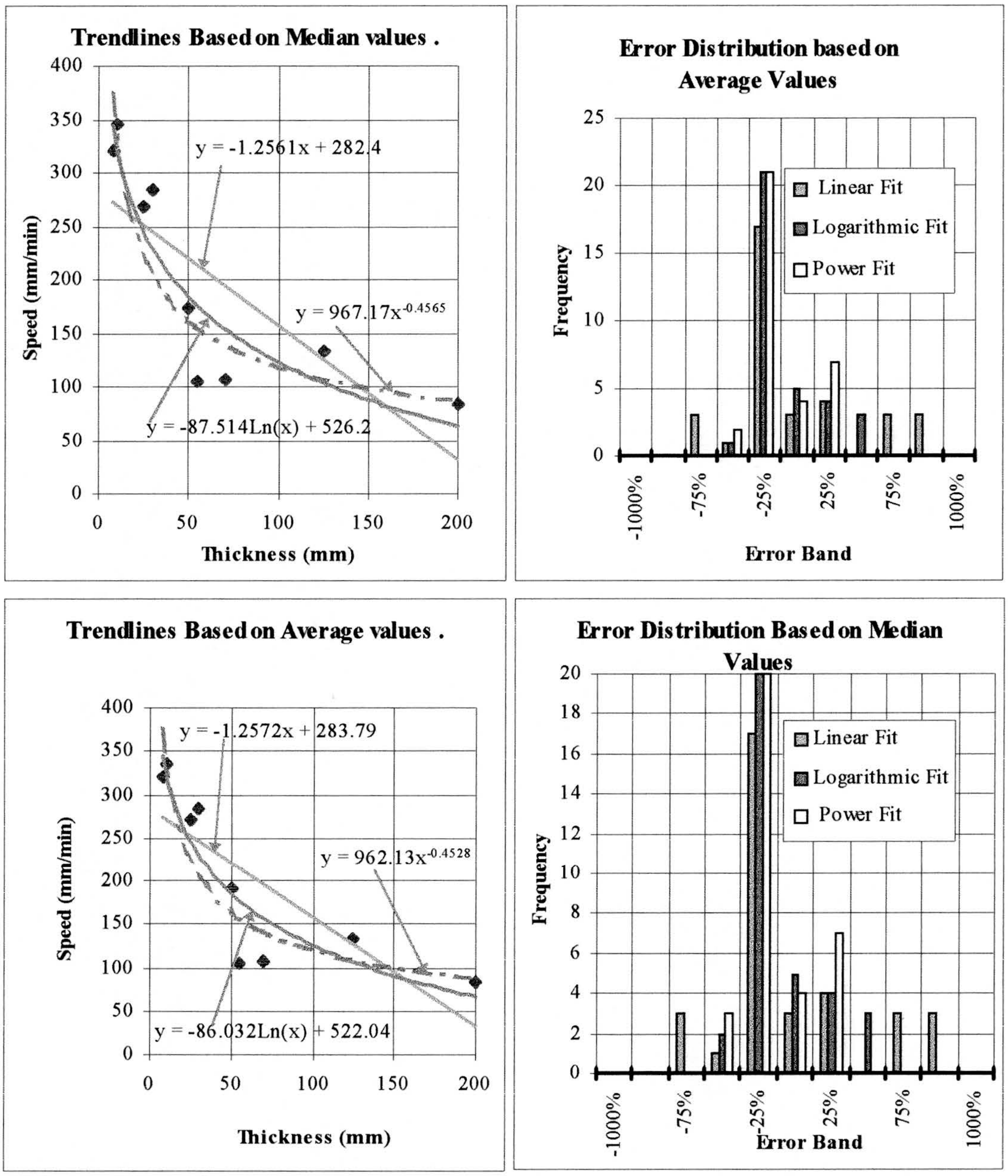

Figure 1.3 Data and Error Distribution Plots for Different Estimation Functions on Average and Median Values

The Equation to Determine the cutting speed is then:

$$\text{CutSpeed} = 967.17 \cdot T^{-0.4565} \cdot \frac{\text{mm}}{\text{min}} \qquad \text{with T in [mm] and } 8 \le T \le 200$$

This equation produced the smallest errors when used to estimate the recorded data. The equation can further never go below 0 when used for estimating cutting speeds for plates thicker than 200mm. The equation will however over estimate the cutting speed for plates thinner than 8mm.

A.1.4. Piercing Time for CNC Flame Profiling with LP-Gas

The piercing time equation was determined by fitting a linear trend line through the median value of piercing time for each specific plate thickness with the least square fit method. The equation is valid for a plate thickness range of 8 mm to 200mm. The linear fit on the median values gave the smallest errors when used to estimate the recorded data.

n	Recorded Time	Seconds	Thickness (mm)	Average Values (s)	Median Values (s)	Error of Linear Fit Based on Average Values	Error of Linear fit Based on Median Values
1	00:24.0	24	8	24	24	27.27%	21.69%
2	00:52.0	52	10	29.5	25	-33.76%	-36.31%
3	00:33.0	33	10			4.37%	0.36%
4	00:21.0	21	10			64.01%	57.70%
5	00:25.0	25	10			37.77%	32.47%
6	00:25.0	25	10			37.77%	32.47%
7	00:21.0	21	10			64.01%	57.70%
8	00:37.0	37	25	37	37	72.11%	68.80%
9	01:26.0	86	50	110.57	113	30.71%	29.48%
10	02:02.0	122	50			-7.86%	-8.73%
11	01:53.0	113	50			-0.52%	-1.46%
12	01:55.0	115	50			-2.25%	-3.17%
13	01:44.0	104	50			8.08%	7.07%
14	01:52.0	112	50			0.36%	-0.58%
15	02:02.0	122	50			-7.86%	-8.73%
16	02:15.0	135	55	136.8	137	-9.52%	-10.27%
17	02:15.0	135	55			-9.52%	-10.27%
18	02:19.0	139	55			-12.12%	-12.86%
19	02:17.0	137	55			-10.84%	-11.58%
20	02:18.0	138	55			-11.48%	-12.23%
21	02:49.0	169	70	145.6	140	-10.42%	-10.97%
22	02:20.0	140	70			8.14%	7.48%
23	02:32.0	152	70			-0.40%	-1.01%
24	02:12.0	132	70			14.69%	13.99%
25	02:15.0	135	70			12.14%	11.46%
26	05:38.0	338	125	335.5	335.5	-23.49%	-23.66%
27	05:33.0	333	125			-22.35%	-22.51%
28	05:59.0	359	200	359	359	12.75%	12.74%
					Average Absolute Error	19.88%	18.85%
					Cumulative Error	-2.22%	-3.05%
					Standard Deviation	27.01%	25.55%
					Median of Error	-0.02%	-0.79%
					Confidence		
					90%	8.40%	7.94%

Table 1.7 Recorded Piercing Time Data With Average and Median Values for Various Material Thicknesses

The piercing times can be summarised as follows :

Thickness (mm)	Seconds	Average Values (s)	Median Values (s)
8	24	24	24
10	52	29.5	25
25	37	37	37
50	86	110.5714	113
55	135	136.8	137
70	169	145.6	140
125	338	335.5	335.5
200	359	359	359

Table 1.8 Median and Average Piercing Times for Various Material Thicknesses

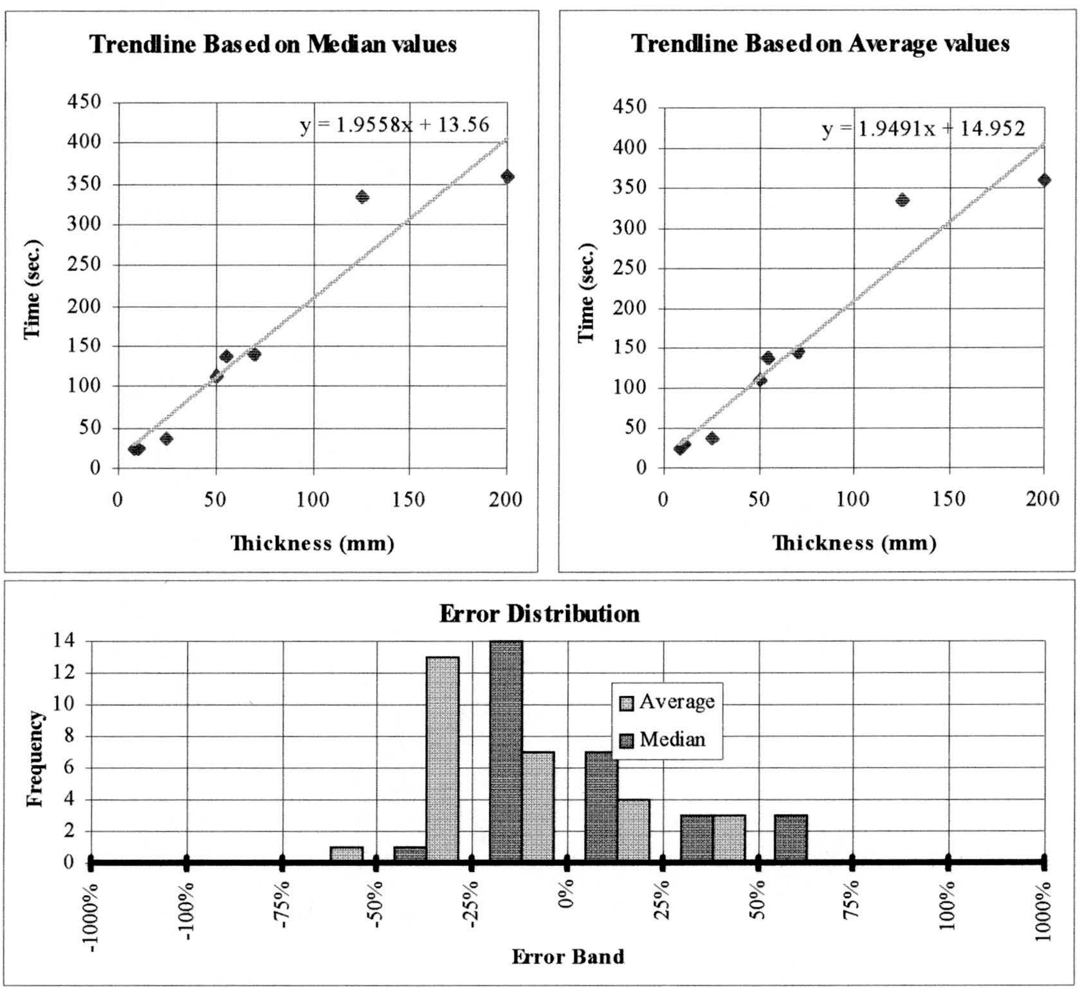

Figure 1.4 Fitted Curves and Error Distribution for Piercing Time Estimation

The piercing time of one pierce hole is then given by :

$$\text{PierceTime} = (1.95 \cdot T + 13.5) \cdot \text{sec} \quad \text{with T in [mm] and } 8 \le T \le 200$$

The linear fit on the median values gave the smallest errors when used to estimate the recorded data.

A.1.5. **Material Set-up for CNC Flame Profile Cutting**

Material Set-up Time =253 seconds. The material set-up time was determined by taking the median of the recorded values. The median value gave the smallest errors when used to predict the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	03:36.0	216	399	253	85%	17%
2	03:10.0	190	399	253	110%	33%
3	04:50.0	290	399	253	38%	-13%
4	15:00.0	900	399	253	-56%	-72%
				Average Absolute Error	71.99%	33.73%
				Cumulative Error	0.00%	-36.59%
				Standard Deviation	73.00%	46.29%
				Median of Error	61.15%	2.19%
				Confidence		
				90%	60.04%	38.07%

Table 1.9 Recorded Material Set-up Data and Calculated Average and Median Values

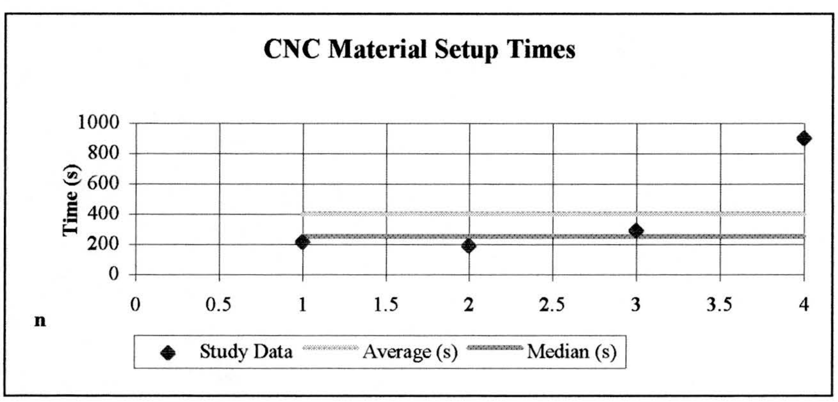

Figure 1.5 Data Plot for Material Set-up

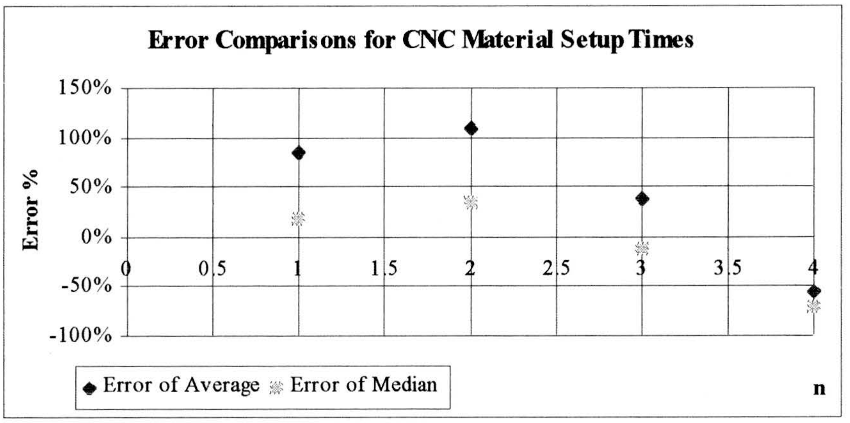

Figure 1.6 Error Plot for Material Set-up

A.1.6. <u>Part Removal Time from CNC Profiling Machine Bed</u>

Part Removal Times = 40 seconds. The part removal time was determined by taking the median of the recorded data. The median value gave the smallest errors when used to predict the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average Values	Error of Median Values
1	00:24.0	24	40.39024	40	68%	67%
2	00:32.0	32	40.39024	40	26%	25%
3	00:22.0	22	40.39024	40	84%	82%
4	00:42.0	42	40.39024	40	-4%	-5%
5	00:21.0	21	40.39024	40	92%	90%
6	00:29.0	29	40.39024	40	39%	38%
7	00:29.0	29	40.39024	40	39%	38%
8	00:38.0	38	40.39024	40	6%	5%
9	00:32.0	32	40.39024	40	26%	25%
10	00:46.0	46	40.39024	40	-12%	-13%
11	00:30.0	30	40.39024	40	35%	33%
12	00:21.0	21	40.39024	40	92%	90%
13	01:25.0	85	40.39024	40	-52%	-53%
14	00:21.0	21	40.39024	40	92%	90%
15	00:28.0	28	40.39024	40	44%	43%
16	00:40.0	40	40.39024	40	1%	0%
17	00:40.0	40	40.39024	40	1%	0%
18	00:55.0	55	40.39024	40	-27%	-27%
19	00:33.0	33	40.39024	40	22%	21%
20	00:28.0	28	40.39024	40	44%	43%
21	00:29.0	29	40.39024	40	39%	38%
22	00:25.0	25	40.39024	40	62%	60%
23	00:30.0	30	40.39024	40	35%	33%
24	00:42.0	42	40.39024	40	-4%	-5%
25	00:45.1	45	40.39024	40	-10%	-11%
26	00:35.0	35	40.39024	40	15%	14%
27	00:43.0	43	40.39024	40	-6%	-7%
28	00:54.0	54	40.39024	40	-25%	-26%

29	00:35.0	35	40.39024	40	15%	14%
30	00:50.0	50	40.39024	40	-19%	-20%
31	00:53.0	53	40.39024	40	-24%	-25%
32	00:50.0	50	40.39024	40	-19%	-20%
33	00:38.0	38	40.39024	40	6%	5%
34	00:48.0	48	40.39024	40	-16%	-17%
35	00:49.0	49	40.39024	40	-18%	-18%
36	01:15.0	75	40.39024	40	-46%	-47%
37	00:56.0	56	40.39024	40	-28%	-29%
38	00:50.0	50	40.39024	40	-19%	-20%
39	00:56.0	56	40.39024	40	-28%	-29%
40	00:47.0	47	40.39024	40	-14%	-15%
41	00:50.0	50	40.39024	40	-19%	-20%
				Avg. Abs. Err.	31.14%	30.77%
				Cumulative Err.	0.00%	-0.97%
				Standard Dev.	38.50%	38.13%
				Median of Error	0.98%	0.00%
				Confidence		
				90%	9.89%	9.80%

Table 1.10 Recorded Data for Part Removal, Average and Median Values

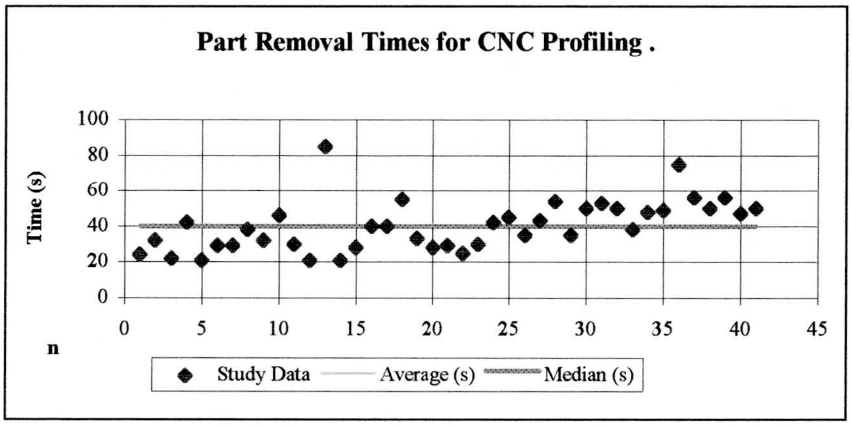

Figure 1.7 Data Plot of Part Removal Times

A.1.7. <u>Part Connection Times with an Electro-Magnet</u>

Connecting Time = 25 seconds. The connecting time with an electro magnet was determined by taking the median values of the recorded data. The median value gave the smallest errors when used to estimate the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:20.7	21	31.333	25	49%	19%
2	01:35.2	95	31.333	25	-67%	-74%
3	00:05.9	6	31.333	25	422%	317%
4	00:20.0	20	31.333	25	57%	25%
5	00:10.0	10	31.333	25	213%	150%

6	00:13.0	13	31.333	25	141%	92%
7	00:12.0	12	31.333	25	161%	108%
8	01:21.0	81	31.333	25	-61%	-69%
9	00:24.0	24	31.333	25	31%	4%
10	00:52.0	52	31.333	25	-40%	-52%
11	00:05.0	5	31.333	25	527%	400%
12	00:45.0	45	31.333	25	-30%	-44%
13	00:13.0	13	31.333	25	141%	92%
14	00:11.0	11	31.333	25	185%	127%
15	00:28.0	28	31.333	25	12%	-11%
16	00:32.0	32	31.333	25	-2%	-22%
17	00:55.0	55	31.333	25	-43%	-55%
18	00:36.0	36	31.333	25	-13%	-31%
19	00:45.0	45	31.333	25	-30%	-44%
20	00:50.5	50	31.333	25	-37%	-50%
21	00:08.0	8	31.333	25	292%	213%
22	00:05.0	5	31.333	25	527%	400%
23	01:02.0	62	31.333	25	-49%	-60%
24	00:25.0	25	31.333	25	25%	0%
25	00:11.0	11	31.333	25	185%	127%
26	00:12.0	12	31.333	25	161%	108%
27	00:24.0	24	31.333	25	31%	4%
28	01:43.0	103	31.333	25	-70%	-76%
29	00:29.0	29	31.333	25	8%	-14%
30	00:47.0	47	31.333	25	-33%	-47%
31	00:28.0	28	31.333	25	12%	-11%
32	00:12.0	12	31.333	25	161%	108%
33	00:25.0	25	31.333	25	25%	0%
34	00:46.0	46	31.333	25	-32%	-46%
35	00:12.0	12	31.333	25	161%	108%
36	00:25.0	25	31.333	25	25%	0%
				Average Absolute Error	112.78%	86.33%
				Cumulative Error	0.00%	-20.21%
				Standard Deviation	156.08%	124.53%
				Median of Error	25.33%	0.00%
				Confidence		
				90%	42.79%	34.14%

Table 1.11 Recorded Connecting Time Data and Average and Median Values

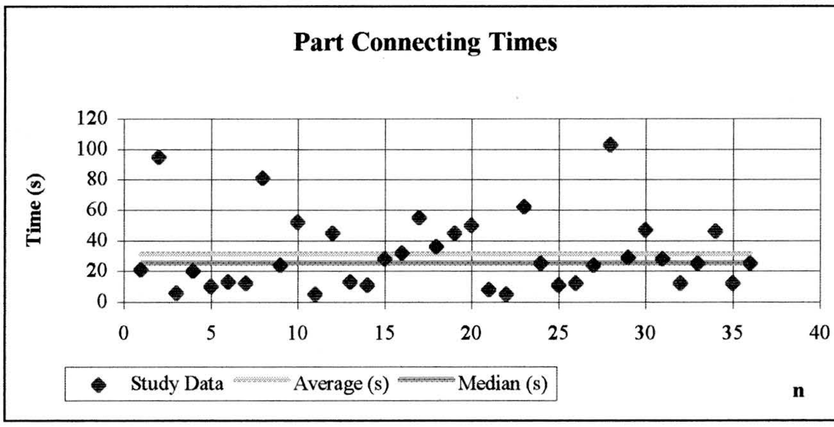

Figure 1.8 Part Connecting Time Plot

A.1.8. Moving with Crane to Machine Bed

Moving Time = 26.5 seconds. The moving back time with a crane was determined by taking the median of the recorded data. The median value gave the smallest overall errors.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average Values	Error of Median values
1	00:23.3	23	30.42105	26.5	32%	15%
2	00:29.8	30	30.42105	26.5	1%	-12%
3	00:25.6	26	30.42105	26.5	17%	2%
4	00:23.1	23	30.42105	26.5	32%	15%
5	00:19.0	19	30.42105	26.5	60%	39%
6	01:00.0	60	30.42105	26.5	-49%	-56%
7	00:54.0	54	30.42105	26.5	-44%	-51%
8	00:59.0	59	30.42105	26.5	-48%	-55%
9	00:27.0	27	30.42105	26.5	13%	-2%
10	00:25.0	25	30.42105	26.5	22%	6%
11	00:26.0	26	30.42105	26.5	17%	2%
12	00:21.0	21	30.42105	26.5	45%	26%
13	00:20.0	20	30.42105	26.5	52%	33%
14	00:32.0	32	30.42105	26.5	-5%	-17%
15	00:18.0	18	30.42105	26.5	69%	47%
16	01:05.7	66	30.42105	26.5	-54%	-60%
17	00:27.0	27	30.42105	26.5	13%	-2%
18	00:25.0	25	30.42105	26.5	22%	6%
19	00:34.0	34	30.42105	26.5	-11%	-22%
20	00:25.0	25	30.42105	26.5	22%	6%
21	00:24.0	24	30.42105	26.5	27%	10%
22	00:19.0	19	30.42105	26.5	60%	39%
23	00:40.0	40	30.42105	26.5	-24%	-34%
24	00:25.4	25	30.42105	26.5	22%	6%
25	00:22.0	22	30.42105	26.5	38%	20%
26	00:22.0	22	30.42105	26.5	38%	20%
27	00:16.0	16	30.42105	26.5	90%	66%
28	00:20.0	20	30.42105	26.5	52%	33%

29	00:28.0	28	30.42105	26.5	9%	-5%
30	00:25.0	25	30.42105	26.5	22%	6%
31	00:27.0	27	30.42105	26.5	13%	-2%
32	00:32.0	32	30.42105	26.5	-5%	-17%
33	00:33.0	33	30.42105	26.5	-8%	-20%
34	00:27.0	27	30.42105	26.5	13%	-2%
35	00:32.0	32	30.42105	26.5	-5%	-17%
36	00:30.0	30	30.42105	26.5	1%	-12%
37	00:38.0	38	30.42105	26.5	-20%	-30%
38	00:56.0	56	30.42105	26.5	-46%	-53%
				Average Absolute Error	29.44%	22.80%
				Cumulative Error	0.00%	-12.89%
				Standard Deviation	34.36%	29.93%
				Median of Error	14.84%	0.04%
				Confidence		
				90%	9.17%	7.99%

Table 1.12 Recorded Data for Crane Movement to and From Machine Bed

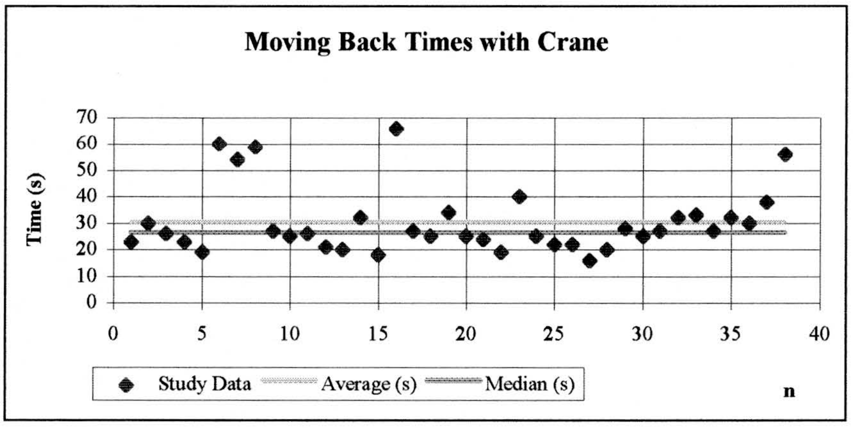

Figure 1.9 Data Plot for Crane Moving

A.1.9. Removing Scrap from the CNC Profiling Machine Bed

Scrap Removal = 73 seconds. Scrap removal was determined by taking the median of the recorded times. The median value gave the smallest errors when used to predict the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average values	Error of Median Values
1	01:13.0	73	67.33333	73	-7.76%	0.00%
2	00:53.0	53	67.33333	73	27.04%	37.74%

3	01:16.0	76	67.33333	73	-11.40%	-3.95%
				Average Absolute Error	15.40%	13.89%
				Cumulative Error	0.00%	8.42%
				Standard Deviation	21.22%	23.01%
				Median of Error	-7.76%	0.00%
				Confidence		
				90%	20.16%	21.85%

Table 1.13 Recorded Data for Scrap Removal from Machine Bed

A.1.10. **<u>Cleaning Time for Pierced Holes for Plate Thicknesses Over 30mm</u>**

Cleaning Time = 10.6 seconds per hole. The cleaning time per hole was determined by taking the median of the recorded data. The median value gave the smallest errors when used to estimate the recorded data.

n	Recorded Time	Seconds	Holes	Time per Hole	Average (s)	Median (s)	Error of Average	Error of Median
1	01:35.0	95	9	10.555556	20.085185	10.555556	90.28%	0.00%
2	01:20.0	80	2	40	20.085185	10.555556	-49.79%	-73.61%
3	01:37.0	97	10	9.7	20.085185	10.555556	107.06%	8.82%
						Average Absolute Error	82.38%	27.48%
						Cumulative error	0.00%	-47.45%
						Standard Deviation	86%	45%
						Median of Error	90%	0%
						Confidence		
						90%	82%	43%

Table 1.14 Recorded Data for Pierce Hole Cleaning

Cleaning is only necessary for plate thickness over 30mm because of metal solidification around the pierced hole.

Appendix B

Grinding Data

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B .1. Recorded and Reduced Data

B .1.1. Grinder Setup Times

Grinder Setup Time = 30 seconds. The grinder setup time was recorded by taking the median of the recorded data. The median gave the smallest errors when used to predict the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:55.0	55	32.9375	30	-40%	-45%
2	00:19.0	19	32.9375	30	73%	58%
3	00:13.0	13	32.9375	30	153%	131%
4	00:10.0	10	32.9375	30	229%	200%
5	00:15.0	15	32.9375	30	120%	100%
6	00:20.0	20	32.9375	30	65%	50%
7	01:43.0	103	32.9375	30	-68%	-71%
8	00:37.0	37	32.9375	30	-11%	-19%
9	00:39.0	39	32.9375	30	-16%	-23%
10	00:44.0	44	32.9375	30	-25%	-32%
11	00:25.0	25	32.9375	30	32%	20%
12	00:16.4	16	32.9375	30	106%	88%
13	00:37.0	37	32.9375	30	-11%	-19%
14	00:13.0	13	32.9375	30	153%	131%
15	00:35.0	35	32.9375	30	-6%	-14%
16	00:46.0	46	32.9375	30	-28%	-35%
				Average Absolute Error	71.03%	64.69%
				Cumulative Error	0.00%	-8.92%
				Standard Deviation	86.01%	78.34%
				Median of Error	12.93%	2.86%
				Confidence		
				90%	35.37%	32.21%

Table 1.1 Recorded Data for Grinder Setup

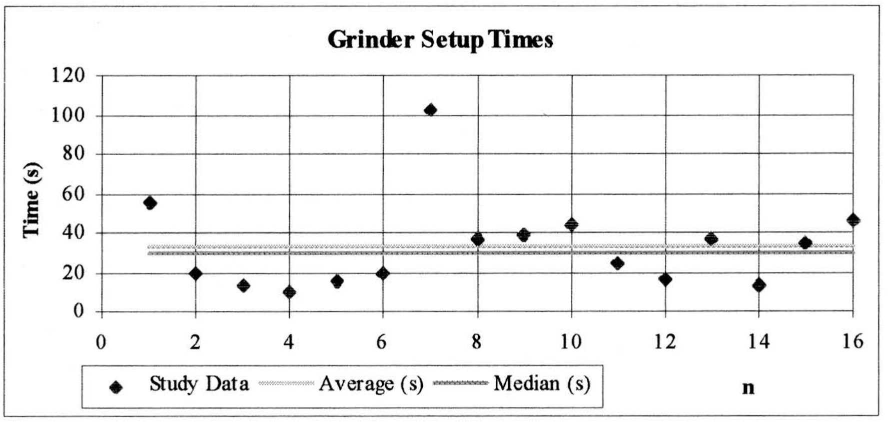

Figure 1.1 Data Plot For Grinder Setup Times

B .1.2. Grinder De-Setup Time

Grinder De-Setup Time = 22 seconds. The grinder de-setup time was determined by taking the median of the recorded times. The median value gave the smallest errors when used to predict the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:40.1	40	24.636364	22	-38.41%	-45.00%
2	00:35.0	35	24.636364	22	-29.61%	-37.14%
3	00:14.0	14	24.636364	22	75.97%	57.14%
4	00:39.0	39	24.636364	22	-36.83%	-43.59%
5	00:50.0	50	24.636364	22	-50.73%	-56.00%
6	00:27.0	27	24.636364	22	-8.75%	-18.52%
7	00:10.0	10	24.636364	22	146.36%	120.00%
8	00:08.0	8	24.636364	22	207.95%	175.00%
9	00:08.0	8	24.636364	22	207.95%	175.00%
10	00:18.0	18	24.636364	22	36.87%	22.22%
11	00:22.0	22	24.636364	22	11.98%	0.00%
				Average Absolute Error	77.40%	68.15%
				Cumulative Error	0.00%	-10.70%
				Standard Deviation	98.34%	87.81%
				Median of Error	11.98%	0.00%
				Confidence		
				90.0%	48.77%	43.55%

Table 1.2 Recorded Data, Average and Median Values for Grinder De-Setup

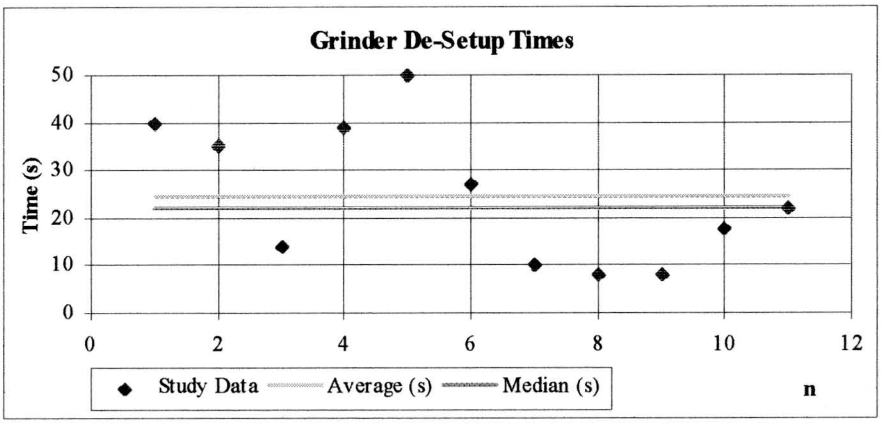

Figure 1.2 Data Plot for Grinder De-Setup Times

B .1.3.<u>**Burr Removal Grinding Speed of CNC Profiled Parts**</u>

Burr Removal Speed = 7041 mm per minute. The burr removal speed was determined by taking the median of the recorded data. The median speed gave the smallest errors when comparing the predicted grinding time to the recorded time.

n	Recorded Time	Second	Length (mm)	Speed (mm/min)	Average (mm/min)	Median (mm/min)	Error of Average	Error of Median
1	03:42.0	222	29760	8043.243	6963.746	7041.52174	16%	14%
2	01:48.0	108	7564.286	4202.381	6963.746	7041.52174	-40%	-40%
3	01:12.0	72	7564.286	6303.571	6963.746	7041.52174	-9%	-10%
4	01:55.0	115	14180	7398.261	6963.746	7041.52174	6%	5%
5	01:32.0	92	10250	6684.783	6963.746	7041.52174	-4%	-5%
6	00:44.0	44	8240	11236.36	6963.746	7041.52174	61%	60%
7	01:34.0	94	14180	9051.064	6963.746	7041.52174	30%	29%
8	00:39.0	39	1630	2507.692	6963.746	7041.52174	-64%	-64%
9	01:51.0	111	14028	7582.703	6963.746	7041.52174	9%	8%
10	02:07.0	127	14028	6627.402	6963.746	7041.52174	-5%	-6%
						Average Absolute Error	24.39%	24.12%
						Cumulative Error	2.17%	1.04%
						Standard Deviation	34.67%	34.29%
						Median of Error	1.12%	0.00%
						Confidence		
						90%	18.03%	17.83%

Table 1.3 Recorded Data, Average and Median Speeds for Burr Removal Grinding

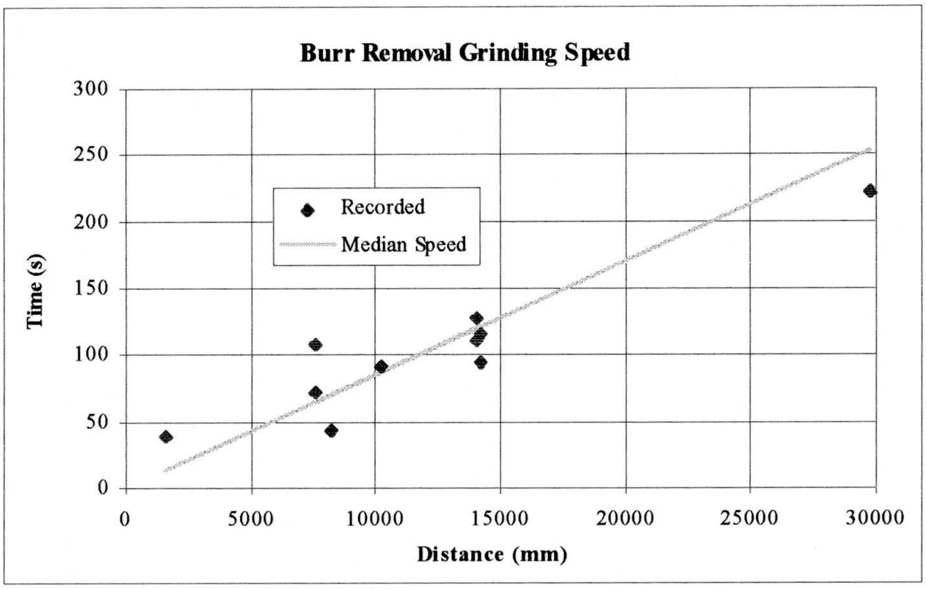

Figure 1.3 Data Plot for Burr Removal Grinding Speed

B .1.4. Surface Cleaning of CNC profiled part edges and Bevelled Edges

B .1.4.1. *Clean Grinding Time for CNC Part Edges & Mech. Bevelled Edges*

Clean Grinding Time (CNC & Mech.)=$7.028 \cdot 10^{-4} \cdot A + 52$ s. with A in [mm^2]

and $9600 \leq A \leq 48000$

The clean grinding speed was determined with the least square fit method of the recorded data. The estimated times predicted with this method gave the smallest errors for the recorded data.

n	Recorded Time	Area (mm^2)	Seconds	Speed (mm^2/min)	Median Speed (mm^2/min)	Least Square Fit Estimated Time (s)	Error of Median	Error of Least Square Fit
1	03:42.0	126000	222	34054.05	35648	140.742724	-4%	-37%
2	00:53.0	9600	53	10867.92	35648	58.942272	-70%	11%
3	01:45.0	126000	105	72000	35648	140.742724	102%	34%
4	02:26.0	126000	146	51780.82	35648	140.742724	45%	-4%
5	00:32.0	9600	32	18000	35648	58.942272	-50%	84%
6	02:27.0	126000	147	51428.57	35648	140.742724	44%	-4%
7	00:35.0	9600	35	16457.14	35648	58.942272	-54%	68%
8	00:26.0	9600	26	22153.85	35648	58.942272	-38%	127%
9	03:23.0	126000	203	37241.38	35648	140.742724	4%	-31%

10	06:00.0	480000	360	80000	35648	389.517293	124%	8%
						Average Absolute Error	53.56%	40.79%
						Cumulative Error	45.44%	0.00%
						Standard Deviation	67.03%	52.54%
						Median of Error	0.00%	9.71%
						Confidence		
						90%	34.86%	27.33%

Table 1.4 Recorded Data, Median Speeds and Least Square Time Estimation for Clean Grinding Time

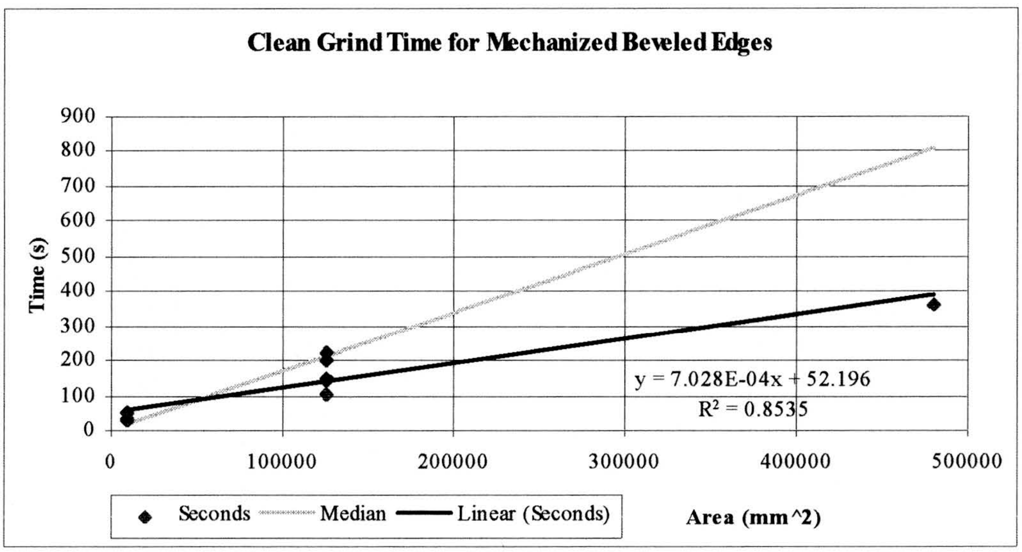

Figure 1.4 Grinding Time vs. Area

B .1.4.2.*Clean Grinding Speed of Manual Bevelled Edges*

Clean Grinding Speed (Man. Bevelled) = 3487.1 square mm per minute. The manual bevelling speed was determined by taking the median of the recorded speeds. The time estimation with the median gave the smallest errors when compared to the recorded data.

n	Recorded Time	Seconds	Length (mm)	Area (mm^2)	Speed (mm^2/min)	Average Speed	Median Speed	Error of Average Speed	Error of Median Speed
1	29:19.0	1759	2729	44755.6	1526.6265	3618.08	3487.11	-58%	-56%
2	23:10.0	1390	2729	44755.6	1931.8964	3618.08	3487.11	-47%	-45%
3	24:36.5	1476	2729	44755.6	1819.3333	3618.08	3487.11	-50%	-48%
4	12:56.0	776	2750	45100	3487.1134	3618.08	3487.11	-4%	0%
5	15:28.0	928	2765	45346	2931.8534	3618.08	3487.11	-19%	-16%

6	05:40.0	340	1745	28618	5050.2353	3618.08	3487.11	40%	45%
7	06:13.0	373	1745	28618	4603.4316	3618.08	3487.11	27%	32%
8	08:04.0	484	2750	45100	5590.9091	3618.08	3487.11	55%	60%
9	08:04.0	484	2765	45346	5621.405	3618.08	3487.11	55%	61%
							Average Absolute Error	39.27%	40.33%
							Cumulative Error	-22.90%	-20.01%
							Standard Deviation	45.70%	47.41%
							Median of Error	-3.62%	0.00%
							Confidence		
							90%	25.05%	26.00%

Table 1.5 Recorded Data, Average and Median Grinding Speeds for Manual Beveled Edges

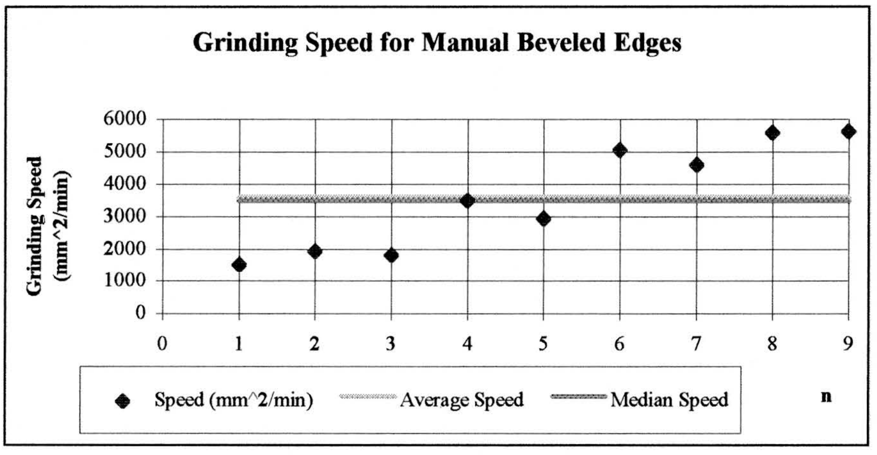

Figure 1.5 Recorded Data Plot of Grinding Speed

B .1.4.3.<u>*Grinding Time Per Disk (Bevelled Edges, CNC Part Edges and Blend Grinding)*</u>

Grinding Time per Disk = 899.5 seconds. The grinding time per disk was determined by taking the median of the recorded times. The median time gave the smallest errors when compared to the recorded times.

n	Grind Time per Disk	Grinding Time (s)	Average of Grinding Time (s)	Median of Grinding Time (s)	Error of Average Grinding Time	Error of Median Grinding Time
1	16:25.0	985	899.5	901	-9%	-9%
2	18:05.0	1085	899.5	901	-17%	-17%
3	10:46.0	646	899.5	901	39%	39%

4	12:23.0	743	899.5	901	21%	21%
5	17:53.0	1073	899.5	901	-16%	-16%
6	19:02.0	1142	899.5	901	-21%	-21%
7	11:45.0	705	899.5	901	28%	28%
8	13:37.0	817	899.5	901	10%	10%
				Average Absolute Error	20.15%	20.18%
				Cumulative Error	0.00%	0.17%
				Standard Deviation	23.22%	23.26%
				Median of Error	0.71%	0.88%
				Confidence		
				90%	13.51%	13.53%

Table 1.6 Recorded Data, Average and Median Grinding Speed for Mech. Bevelled Edges

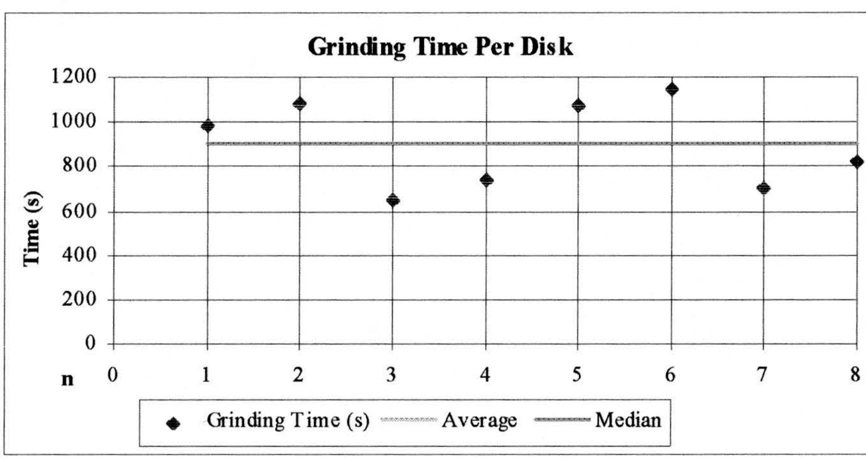

Figure 1.6 Recorded Data Plot of Grinding Time Per Disk

B .1.4.4.*Grinding Disk Change Time*

Disk Change Time = 107 seconds. The grinding disk change time was determined by taking the median of the recorded data. The median time gave the smallest errors when used to estimate the recorded data.

n	Recorded Disk Change Time	Seconds Changing Time	Average of Changing Time (s)	Median of Changing Time (s)	Error of Average Changing Time	Error of Median Changing Time
1	03:34.0	214	116.5	107	-46%	-50%
2	01:16.0	76	116.5	107	53%	41%

3	01:49.0	109	116.5	107	7%	-2%
4	02:29.0	149	116.5	107	-22%	-28%
5	01:25.0	85	116.5	107	37%	26%
6	01:14.0	74	116.5	107	57%	45%
7	02:00.0	120	116.5	107	-3%	-11%
8	01:45.0	105	116.5	107	11%	2%
				Average Absolute Error	29.49%	25.50%
				Cumulative Error	0.00%	-8.15%
				Standard Deviation	36.06%	33.12%
				Median of Error	8.92%	0.03%
				Confidence		
				90%	20.97%	19.26%

Table 1.7 Recorded, Average and Median Grinding Disk Change Times

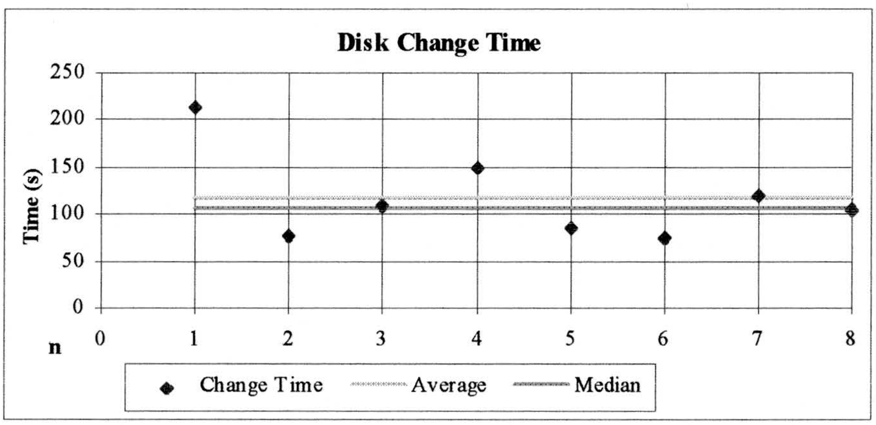

Figure 1.7 Recorded Data Plot of Disk Change Time

B .1.5. Back Grinding Time Constants and Formula

B .1.5.1. *Back Grinding Cool Down Time Ratio*

Ratio =1.0359 (grind/cool down). This ratio is the grinding time divided by the cool-down time. The cool down ratio was determined by taking the median of the recorded data. The median value gave the smallest errors when used to predict the recorded cool down times.

n	Grinding Time	Cooling Time	Ratio	Average Ratio	Median Ratio	Error of Average	Error of Median
1	06:50.0	19:14.0	0.35529	1.08344	1.0359	205%	192%
2	21:21.4	20:37.0	1.03589	1.08344	1.0359	5%	0%
3	34:15.2	20:30.0	1.67089	1.08344	1.0359	-35%	-38%

4	15:05.2	12:04.6	1.24924	1.08344	1.0359	-13%	-17%
5	15:19.0	17:20.0	0.88365	1.08344	1.0359	23%	17%
6	35:37.2	18:06.0	1.96796	1.08344	1.0359	-45%	-47%
7	12:57.0	30:45.0	0.42114	1.08344	1.0359	157%	146%
					Average Absolute Error	68.97%	65.32%
					Cumulative Error	0.00%	-4.39%
					Standard Deviation	98.47%	94.15%
					Median of Error	4.59%	0.00%
					Confidence		
					90%	61.22%	58.53%

Table 1.8 Recorded, Average and Median Grind/Cool Ratios

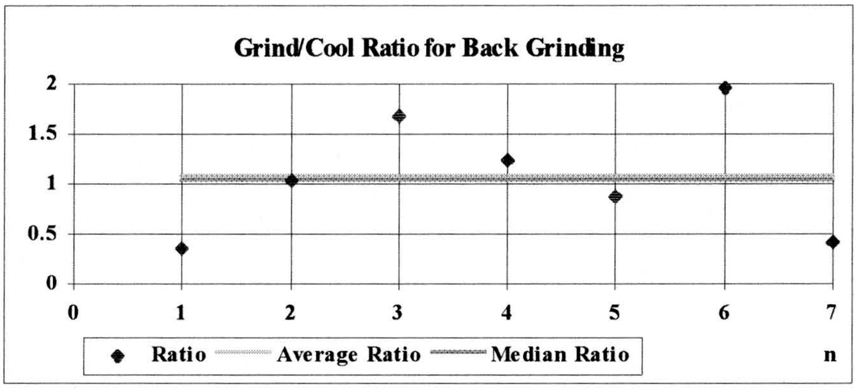

Figure 1.8 Recorded Data Plot

B .1.5.2.*Back Grinding Speed*

The back grinding speed was determined by taking the median and average of the recorded data for various grinding depths. A linear and power fit were then constructed on the median and average points with the least square method. The formula that predicted the smallest errors were then taken to estimate the grinding speed. The errors were also determined for the median and average speed of all the recorded data points.

n	Recorded Time	Seconds	Length (mm)	Speed (mm/min)	Thickness of Material (mm)	Average (s)	Median (s)
1	10:05.0	605	1710	169.587	8	194.739	190.286
2	05:19.0	319	1100	206.897	8		

3	04:50.0	290	1110	229.655	8		
4	05:50.0	350	1110	190.286	8		
5	03:40.0	220	650	177.273	8		
6	0:04	257	339	79.144	15	90.3502	90.3502
7	08:34.0	514	870	101.556	15		
8	2:13	7996	9524	71.4657	25	76.442	78.527
9	2:02	7320	6415	52.582	25		
10	08:52.0	532	780	87.9699	25		
11	11:20.0	680	970	85.5882	25		
12	08:44.0	524	790	90.458	25		
13	19:33.0	1173	1380	70.5882	25		
			Average of Measured Speed	124.081			
			Median of Measured Speed	90.458			

Table 1.9 Recorded, Average and Median Back Grinding Speeds at Various Depths

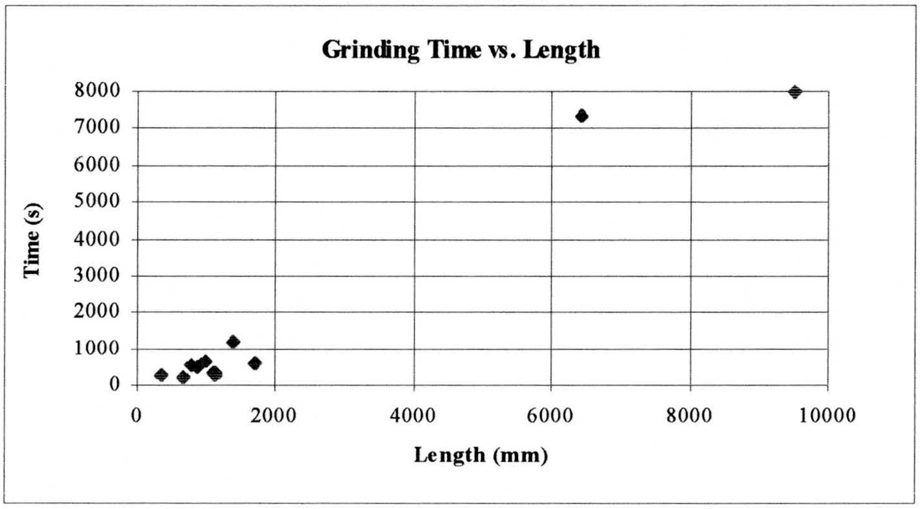

Figure 1.9 Grinding Time vs. Length

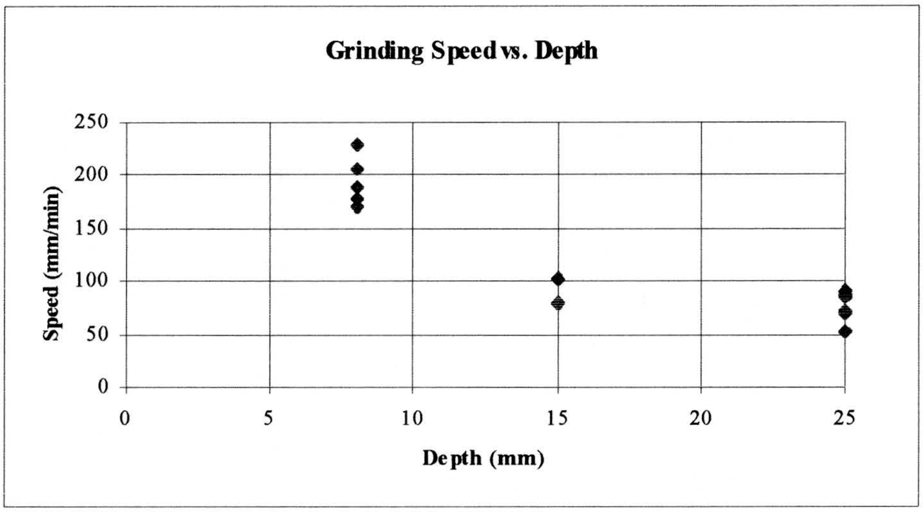

Figure 1.10 Grinding Speed vs. Grinding Depth

n	Error of Average Speed Based on all Data Points	Error of Median Speed Based on all Data Point	Error of Linear fit Based on The Average Speed	Error of Power fit Based on The Average Speed	Error of Linear fit Based on The Median Speed	Error of Power fit Based on The Median Speed
1	-13%	-11%	-2%	-6%	0%	-4%
2	6%	9%	20%	15%	22%	17%
3	18%	21%	33%	27%	36%	30%
4	-2%	0%	10%	5%	12%	8%
5	-9%	-7%	2%	-2%	5%	1%
6	-12%	-12%	-38%	-26%	-37%	-26%
7	12%	12%	-20%	-5%	-19%	-5%
8	-7%	-9%	17%	3%	12%	0%
9	-31%	-33%	-14%	-25%	-18%	-26%
10	15%	12%	43%	26%	38%	23%
11	12%	9%	40%	23%	34%	20%
12	18%	15%	48%	30%	42%	27%
13	-8%	-10%	15%	1%	10%	-1%

Table 1.10 Errors Produced by Each Fit for Estimating Back Grinding Time

	Average Speed Based on all Data Points	Median Speed Based on all Data Point	Linear Fit Based on Average Speed	Power fit Based on Average Speed	Linear Fit Based on Median Speed	Power Based on the Median Speed
Average Absolute Error	12.61%	12.33%	23.14%	14.85%	21.91%	14.49%
Cumulative Error	-12.70%	-14.50%	5.73%	-5.38%	2.22%	-7.23%
Standard Deviation	15.01%	15.02%	25.84%	18.44%	24.37%	18.33%
Median of Error	-2.29%	0.00%	15.12%	2.54%	11.87%	0.55%
Confidence						
90%	6.85%	6.85%	11.79%	8.41%	11.12%	8.36%

Table 1.11 Summary of Errors Produced by Each Fit for Estimating The Grinding Time

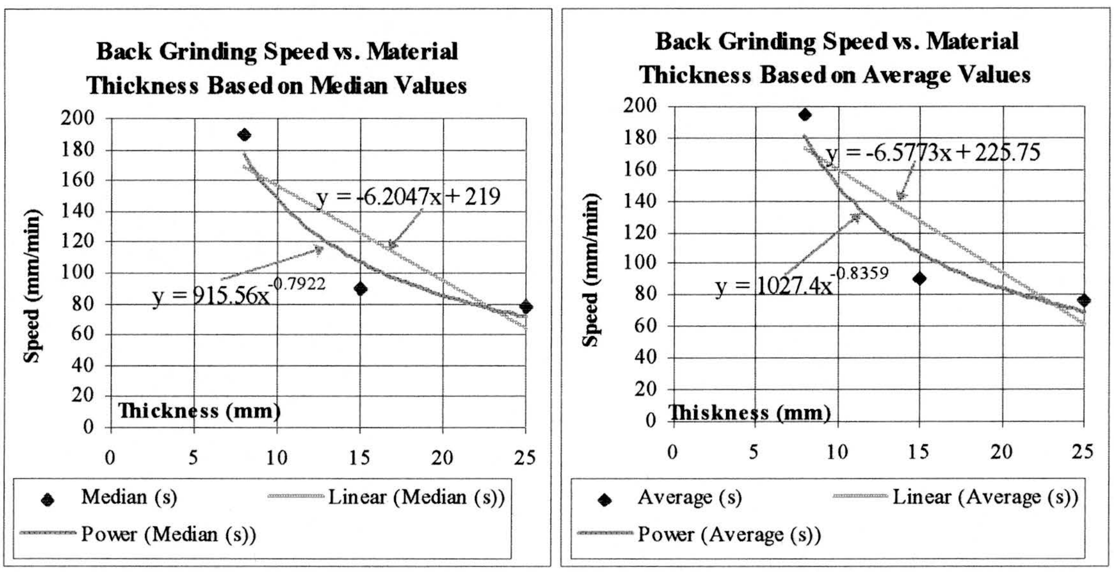

Figure 1.11 Least Square Fits on Average and Median Values

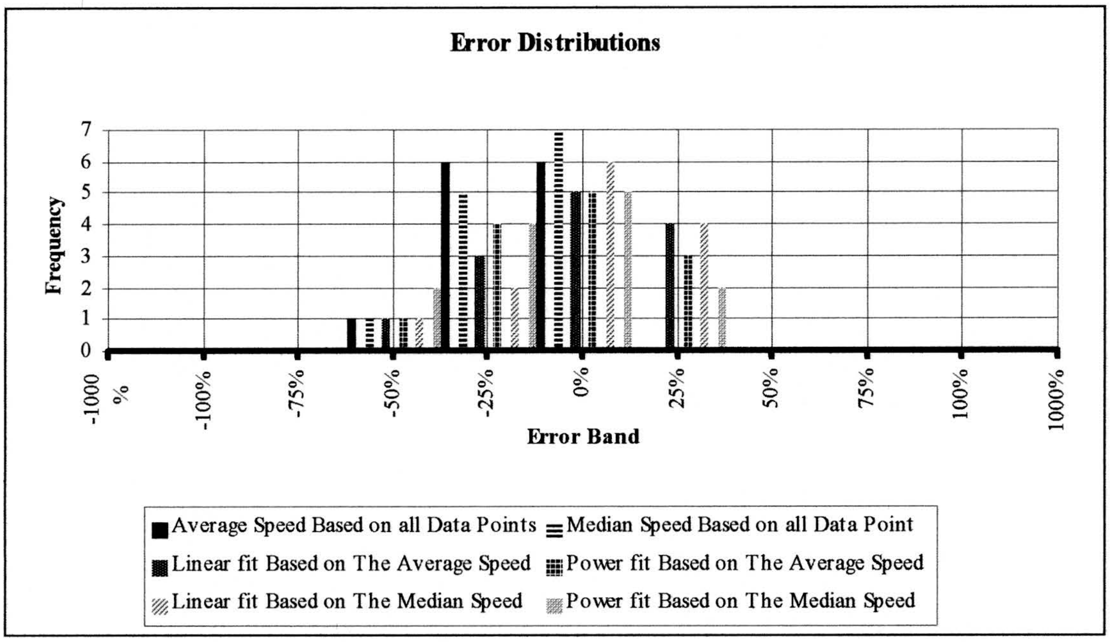

Figure 1.12 Error Distribution of Different Fits for estimating the Grinding Time

The formula to estimate the grinding speed is therefore :

$$GrindSpeed = 1585.5D^{-0.7922}\cdot\frac{mm}{min} \quad \text{With D in [mm] and } 8 \le D \le 25$$

The power fit on the median values gave the smallest errors. This fit will not go below 0 if the one extrapolates to deeper depths.

B .1.5.3. *Grinding Operator Limit for Back Grinding*

Operator Limit = 363.5 seconds. The operator limit was determined by taking the median of the recorded times. The median gave the smallest errors when used to predict the recorded times.

N	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	09:32.7	573	461.969	363.5	-19%	-37%
2	07:04.5	424	461.969	363.5	9%	-14%
3	06:17.0	377	461.969	363.5	23%	-4%
4	02:41.0	161	461.969	363.5	187%	126%
5	05:50.0	350	461.969	363.5	32%	4%
6	08:16.0	496	461.969	363.5	-7%	-27%
7	04:15.0	255	461.969	363.5	81%	43%
8	09:15.0	555	461.969	363.5	-17%	-35%
9	09:00.0	540	461.969	363.5	-14%	-33%
10	07:45.0	465	461.969	363.5	-1%	-22%
11	03:28.0	208	461.969	363.5	122%	75%
12	03:48.0	228	461.969	363.5	103%	59%
13	05:42.0	342	461.969	363.5	35%	6%

14	09:50.0	590	461.969	363.5	-22%	-38%
15	05:45.0	345	461.969	363.5	34%	5%
16	17:40.0	1060	461.969	363.5	-56%	-66%
17	06:50.0	410	461.969	363.5	13%	-11%
18	21:21.4	1281	461.969	363.5	-64%	-72%
19	11:01.1	661	461.969	363.5	-30%	-45%
20	03:02.9	183	461.969	363.5	152%	99%
21	14:14.0	854	461.969	363.5	-46%	-57%
22	03:45.0	225	461.969	363.5	105%	62%
23	15:05.2	905	461.969	363.5	-49%	-60%
24	04:17.0	257	461.969	363.5	80%	41%
25	03:35.0	215	461.969	363.5	115%	69%
26	20:30.0	1230	461.969	363.5	-62%	-70%
27	06:40.0	400	461.969	363.5	15%	-9%
28	05:40.0	340	461.969	363.5	36%	7%
29	02:59.0	179	461.969	363.5	158%	103%
30	04:50.0	290	461.969	363.5	59%	25%
31	04:23.0	263	461.969	363.5	76%	38%
32	02:01.0	121	461.969	363.5	282%	200%
				Average Absolute Error	65.75%	48.80%
				Cumulative Error	0.00%	-21.32%
				Standard Deviation	80.91%	63.67%
				Median of Error	27.26%	0.14%
				Confidence		
				90%	23.53%	18.51%

Table 1.12 Recorded, Average and Median Operator Limit

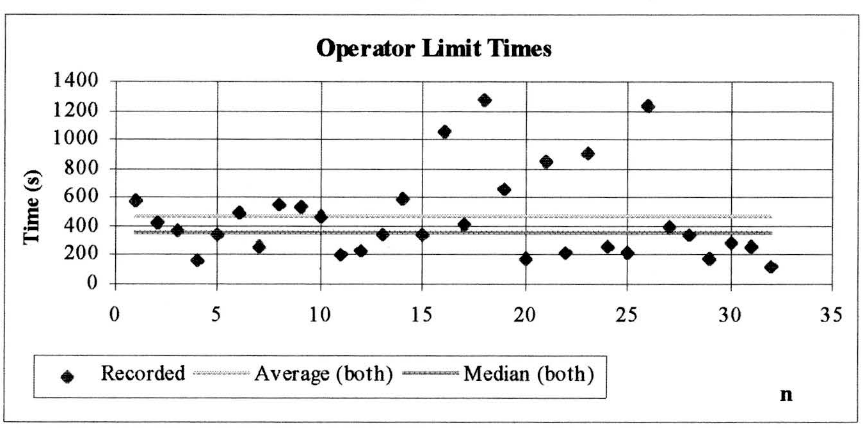

Figure 1.13 Recorded Operator Limit of Two Operators

B .1.6. **Surface Grinding of Welded Sections**

B .1.6.1. *Blend Grinding Speed*

Blend Grind Speed = 3425.3 square mm per minute. The blend grinding speed was determined by taking the median of the recorded speeds. The median predicted times gave the smallest errors.

n	Recorded Time	Seconds	Length (mm)	Area (mm^2)	Speed (mm^2/min)	Average (mm^2/min)	Median (mm^2/min)	Error of Average	Error of Median
1	04:36.0	276	1155	40425	8788	3700	3425.3	138%	157%
2	03:57.0	237	570	19950	5050.6	3700	3425.3	37%	47%
3	03:28.0	208	520	18200	5250	3700	3425.3	42%	53%
4	03:05.0	185	650	22750	7378.4	3700	3425.3	99%	115%
5	03:10.0	190	680	23800	7515.8	3700	3425.3	103%	119%
6	19:56.0	1196	1250	68750	3449	3700	3425.3	-7%	1%
7	18:26.0	1106	1215	66825	3625.2	3700	3425.3	-2%	6%
8	09:51.0	591	860	47300	4802	3700	3425.3	30%	40%
9	09:26.0	566	830	45650	4839.2	3700	3425.3	31%	41%
10	16:15.0	975	1005	55275	3401.5	3700	3425.3	-8%	-1%
11	16:41.0	1001	950	52250	3131.9	3700	3425.3	-15%	-9%
12	11:02.0	662	750	41250	3738.7	3700	3425.3	1%	9%
13	15:42.0	942	990	54450	3468.2	3700	3425.3	-6%	1%
14	12:47.0	767	720	39600	3097.8	3700	3425.3	-16%	-10%
15	14:01.0	841	940	51700	3688.5	3700	3425.3	0%	8%
16	11:11.0	671	670	36850	3295.1	3700	3425.3	-11%	-4%
17	15:40.0	940	715	32175	2053.7	3700	3425.3	-44%	-40%
18	16:43.0	1003	890	40050	2395.8	3700	3425.3	-35%	-30%
19	18:01.0	1081	585	26325	1461.1	3700	3425.3	-61%	-57%
20	17:20.0	1040	725	32625	1882.2	3700	3425.3	-49%	-45%
21	21:29.0	1289	805	36225	1686.2	3700	3425.3	-54%	-51%
22	21:30.0	1290	785	35325	1643	3700	3425.3	-56%	-52%
23	22:11.0	1331	840	37800	1704	3700	3425.3	-54%	-50%
24	09:52.0	592	640	28800	2918.9	3700	3425.3	-21%	-15%
25	09:42.0	582	470	21150	2180.4	3700	3425.3	-41%	-36%
26	02:20.0	140	250	8750	3750	3700	3425.3	1%	9%
							Average Absolute Error	37.04%	38.73%
							Cumulative Error	-21.99%	-15.73%
							Standard Deviation	51.20%	55.30%
							Median of Error	-7.42%	0.00%
							Confidence		
							90%	16.52%	17.84%

Table 1.13 Recorded, Average and Median Blend Grinding Speeds

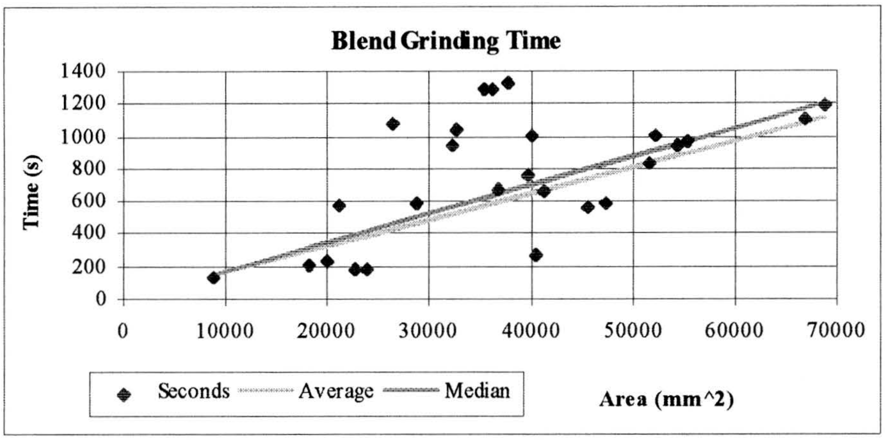

Figure 1.14 Recorded Data Plot of Blend Grinding Speeds

B .1.6.2.*Surface Polishing Speed*

Polish Speed = 14199 square mm per minute. The surface polish speed was determined by taking the median of the recorded speeds. The median value gave the smallest errors when used to estimate the recorded polish times.

n	Recorded Time	Seconds	Length (mm)	Area (mm^2)	Speed (mm^2/min)	Average (mm^2/min)	Median (mm^2/min)	Error of Average	Error of Median
1	03:49.0	229	1090	59950	15707	13404	14199	17%	11%
2	02:38.0	158	760	41800	15873	13404	14199	18%	12%
3	03:10.0	190	910	50050	15805	13404	14199	18%	11%
4	04:11.0	251	1080	59400	14199	13404	14199	6%	0%
5	02:07.0	127	690	37950	17929	13404	14199	34%	26%
6	03:08.0	188	730	40150	12814	13404	14199	-4%	-10%
7	02:28.0	148	600	33000	13378	13404	14199	0%	-6%
8	01:54.0	114	650	35750	18816	13404	14199	40%	33%
9	04:08.0	248	1260	69300	16766	13404	14199	25%	18%
10	03:39.0	219	650	29250	8013.7	13404	14199	-40%	-44%
11	04:54.0	294	810	36450	7438.8	13404	14199	-45%	-48%
12	05:49.0	349	1080	48600	8355.3	13404	14199	-38%	-41%
13	04:40.0	280	950	42750	9160.7	13404	14199	-32%	-35%

Average Absolute Error	24.41%	22.61%
Cumulative Error	-6.41%	- 11.65%
Standard Deviation	29.48%	27.83%
Median of Error	5.93%	0.00%
Confidence		
90%	13.45%	12.69%

Table 1.14 Recorded, Average and Median Polishing Speed

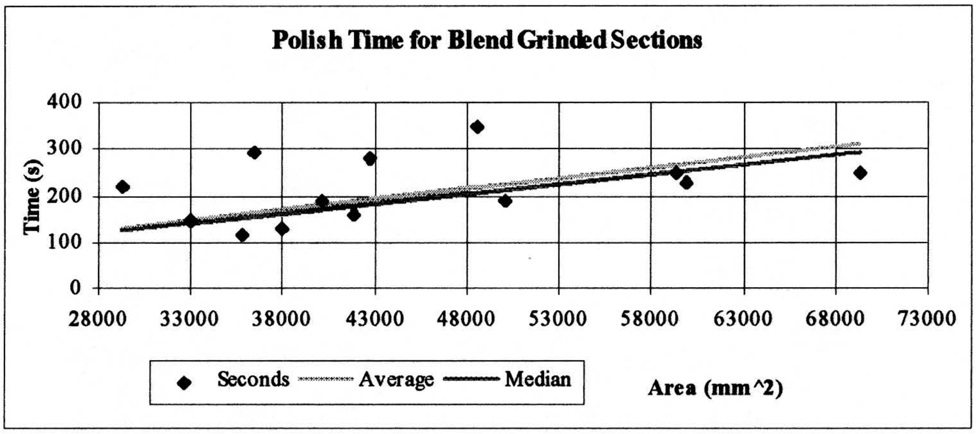

Figure 1.15 Recorded Polishing Time Plot vs. Area

Appendix C

Manual and Mechanised Bevelling Data

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C.1. Recorded and Reduced Time Data for Mechanised Bevelling

C.1.1. Setup Time for Mechanised Bevelling

Mechanised Bevel Setup Time = 91.5 seconds. The mechanised bevelling setup time was determined by taking the median of the recorded setup times. The median value gave the smallest average error and the best confidence.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	03:29.9	210	113.6667	91.5	-45.87%	-56.43%
2	01:17.0	77	113.6667	91.5	47.62%	18.83%
3	01:34.0	94	113.6667	91.5	20.92%	-2.66%
4	01:31.0	91	113.6667	91.5	24.91%	0.55%
5	01:23.0	83	113.6667	91.5	36.95%	10.24%
6	01:44.0	104	113.6667	91.5	9.29%	-12.02%
7	01:59.0	119	113.6667	91.5	-4.48%	-23.11%
8	05:46.0	346	113.6667	91.5	-67.15%	-73.55%
9	02:13.0	133	113.6667	91.5	-14.54%	-31.20%
10	01:15.0	75	113.6667	91.5	51.56%	22.00%
11	00:42.0	42	113.6667	91.5	170.63%	117.86%
12	02:05.0	125	113.6667	91.5	-9.07%	-26.80%
13	01:18.0	78	113.6667	91.5	45.73%	17.31%
14	01:07.0	67	113.6667	91.5	69.65%	36.57%
15	01:23.0	83	113.6667	91.5	36.95%	10.24%
16	01:32.0	92	113.6667	91.5	23.55%	-0.54%
17	02:45.0	165	113.6667	91.5	-31.11%	-44.55%
18	01:02.0	62	113.6667	91.5	83.33%	47.58%
				Average Absolute Error	44.07%	30.67%
				Cumulative Error	0.00%	-19.50%
				Standard Deviation	53.72%	43.24%
				Median of Error	24.23%	0.00%
				Confidence		
				90%	20.83%	16.77%

Table 1.1 Recorded, Average and Median Setup Time

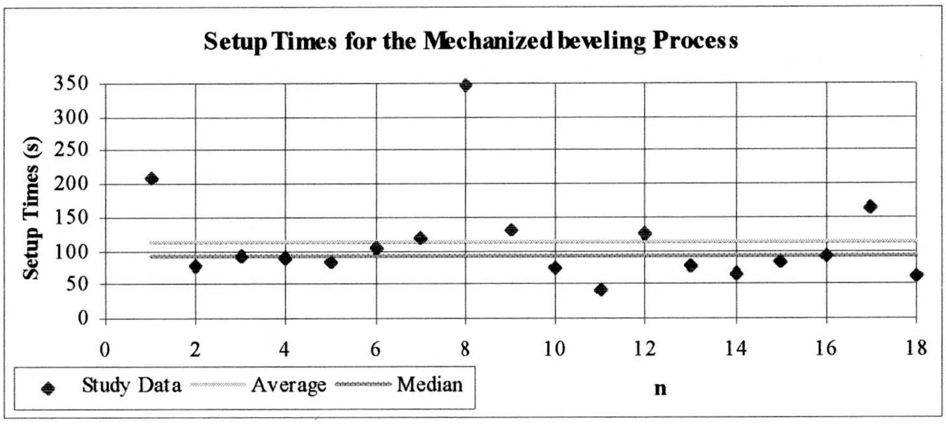

Figure 1.1 Recorded Data Plot for Mech. Bevelling Setup Time

C.1.2. **De-Setup Time For Mechanised Bevelling**

Mechanised Bevelling De-Setup Time = 13.5 seconds. The de-setup time was determined by taking the median of the recorded data. The median value gave the smallest average absolute error and the best confidence.

n	Recorded Time	Second	Average (s)	Median (s)	Error of Average	Error of Median
1	00:39.5	39	17.2	13.5	55.90%	-65.38%
2	00:05.0	5	17.2	13.5	-244.00%	170.00%
3	00:15.0	15	17.2	13.5	-14.67%	-10.00%
4	00:12.0	12	17.2	13.5	-43.33%	12.50%
5	00:07.0	7	17.2	13.5	-145.71%	92.86%
6	00:06.0	6	17.2	13.5	-186.67%	125.00%
7	00:08.4	8	17.2	13.5	-115.00%	68.75%
8	00:38.7	39	17.2	13.5	55.90%	-65.38%
9	00:18.0	18	17.2	13.5	4.44%	-25.00%
10	00:23.0	23	17.2	13.5	25.22%	-41.30%
				Average Absolute Error	89.08%	67.62%
				Cumulative Error	0.00%	-21.51%
				Standard Deviation	105.87%	83.10%
				Median of Error	-29.00%	1.25%
				Confidence		
				90%	55.07%	43.22%

Table 1.2 Recorded, Average and Median De-Setup Times

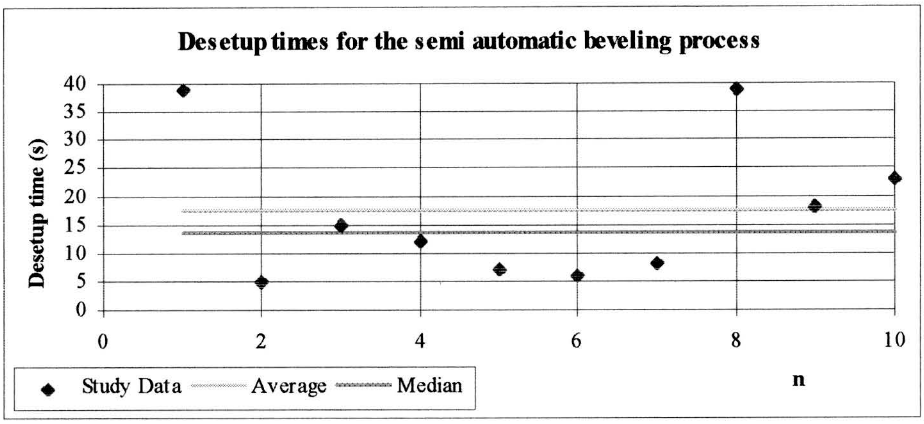

Figure 1.2 Recorded Data Plot of De-Setup Time

C.1.3. Mechanised Bevelling Cut Time

Mechanised Bevelling Speed = $0.2234 \cdot L+27$ with L in[mm] and $140 \leq L \leq 2451$. The bevelling speed was determined wit a robust data analysis of the recorded data , the study could find no correlation between bevel size and bevelling speed. The robust data analysis gave the smallest errors when used predict the recorded bevelling times.

n	Time	Length mm	Seconds	Size (mm)	Beveling Speed (mm/min)	Median Speed (mm/min)	Robust Fit Estimated Time	Error of Median	Error of Robust
1	01:01.2	140	61	7.071	137.7049	205	58.643543	-32.83%	-3.86%
2	01:21.0	178	81	7.071	131.8519	205	67.132667	-35.68%	-17.12%
3	01:18.0	178	78	7.071	136.9231	205	67.132667	-33.21%	-13.93%
4	01:05.0	140	65	7.071	129.2308	205	58.643543	-36.96%	-9.78%
5	00:59.6	140	60	7.071	140	205	58.643543	-31.71%	-2.26%
6	01:21.0	178	81	7.071	131.8519	205	67.132667	-35.68%	-17.12%
7	00:59.0	140	59	7.071	142.3729	205	58.643543	-30.55%	-0.60%
8	10:40.8	2451	641	11.314	229.4228	205	574.91632	11.91%	-10.31%
9	09:27.0	2451	567	11.314	259.3651	205	574.91632	26.52%	1.40%
10	06:43.0	1841	403	7.071	274.0943	205	438.64354	33.70%	8.84%
11	06:50.0	1841	410	7.071	269.4146	205	438.64354	31.42%	6.99%
12	07:20.0	1841	440	7.071	251.0455	205	438.64354	22.46%	-0.31%
13	06:19.0	1841	379	7.071	291.4512	205	438.64354	42.17%	15.74%
14	03:32.0	955	212	7.071	270.283	205	240.71291	31.85%	13.54%
15	00:59.0	140	59	7.071	142.3729	205	58.643543	-30.55%	-0.60%
16	03:30.0	955	210	7.071	272.8571	205	240.71291	33.10%	14.63%
17	03:32.0	955	212	7.071	270.283	205	240.71291	31.85%	13.54%
18	02:58.0	955	178	7.071	321.9101	205	240.71291	57.03%	35.23%
19	03:58.0	955	238	7.071	240.7563	205	240.71291	17.44%	1.14%
20	04:44.0	925	284	18.082	195.4225	205	234.01097	-4.67%	-17.60%
21	09:10.0	1758	550	14.142	191.7818	205	420.10151	-6.45%	-23.62%
22	09:28.0	1720	568	9.434	181.6901	205	411.61238	-11.37%	-27.53%
23	04:29.0	925	269	18.082	206.3197	205	234.01097	0.64%	-13.01%
24	09:20.0	1685	560	9.434	180.5357	205	403.79345	-11.93%	-27.89%

25	04:38.0	925	278	18.082	199.6403	205	234.01097	-2.61%	-15.82%
26	01:12.0	245	72	14.142	204.1667	205	82.100333	-0.41%	14.03%
27	01:12.0	245	72	14.142	204.1667	205	82.100333	-0.41%	14.03%
28	01:12.0	246	72	15.142	205	205	82.323731	0.00%	14.34%
29	04:28.0	925	268	18.082	207.0896	205	234.01097	1.02%	-12.68%
30	01:09.0	245	69	14.142	213.0435	205	82.100333	3.92%	18.99%
31	04:30.0	925	270	18.082	205.5556	205	234.01097	0.27%	-13.33%
							Average Absolute Error	20.98%	12.90%
							Cumulative Error	9.46%	-5.53%
							Standard Deviation	26.59%	15.52%
							Median of Error	0.00%	-0.60%
							Confidence		
							90%	7.85%	4.59%

Table 1.3 Recorded, Median Bevelling Speed and Robust Times

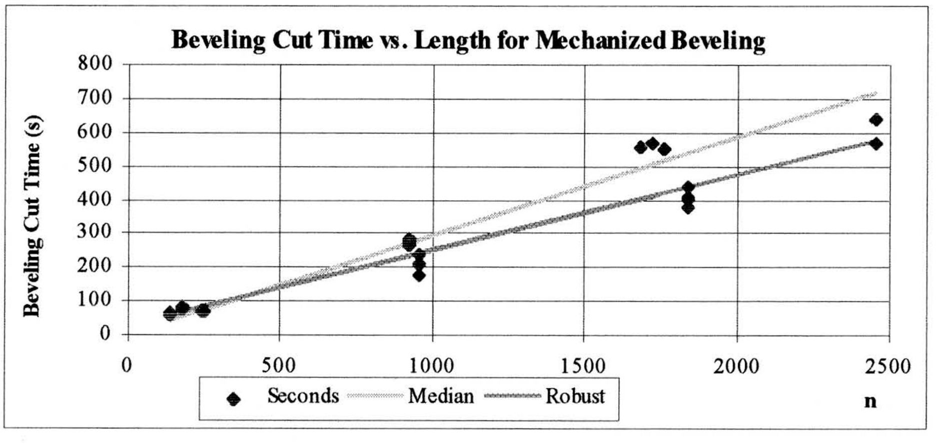

Figure 1.3 Recorded Data Plot for Mechanised Bevelling Cut Time

C.1.4. <u>Burr Cleaning Time for Mechanised Bevelled Edges</u>

Burr Cleaning Time = 0.01·L+18 with L in [mm] and 140≤L≤2451. The burr cleaning speed was determined with robust data analysis of the recorded data. The robust analysis gave the smallest errors when used to estimate the recorded times.

n	Time	Distance (mm)	Seconds	Speed (mm/min)	Median (mm/min)	Robust Estimated Time (s)	Error of Median	Error of Robust
1	00:15.3	140	15	560	970.9091	19.2517669	-42.32%	28.35%
2	00:32.0	178	32	333.75	970.9091	19.6299582	-65.63%	-38.66%
3	00:32.0	178	32	333.75	970.9091	19.6299582	-65.63%	-38.66%
4	00:14.0	140	14	600	970.9091	19.2517669	-38.20%	37.51%
5	00:17.0	140	17	494.11765	970.9091	19.2517669	-49.11%	13.25%

6	00:11.0	178	11	970.90909	970.9091	19.6299582	0.00%	78.45%
7	02:12.0	2451	132	1114.0909	970.9091	42.2517669	14.75%	-67.99%
8	00:54.5	955	54	1061.1111	970.9091	27.3629742	9.29%	-49.33%
9	00:30.0	2451	30	4902	970.9091	42.2517669	404.89%	40.84%
10	00:22.0	955	22	2604.5455	970.9091	27.3629742	168.26%	24.38%
11	00:38.0	2451	38	3870	970.9091	42.2517669	298.60%	11.19%
12	00:32.0	955	32	1790.625	970.9091	27.3629742	84.43%	-14.49%
13	00:14.6	140	15	560	970.9091	19.2517669	-42.32%	28.35%
						Average Absolute Error	98.72%	36.26%
						Cumulative Error	57.45%	-22.36%
						Standard Deviation	149.90%	42.59%
						Median of Error	0.00%	13.25%
						Confidence		
						90%	68.39%	19.43%

Table 1.4 Recorded, Average and Median Cleaning Speeds

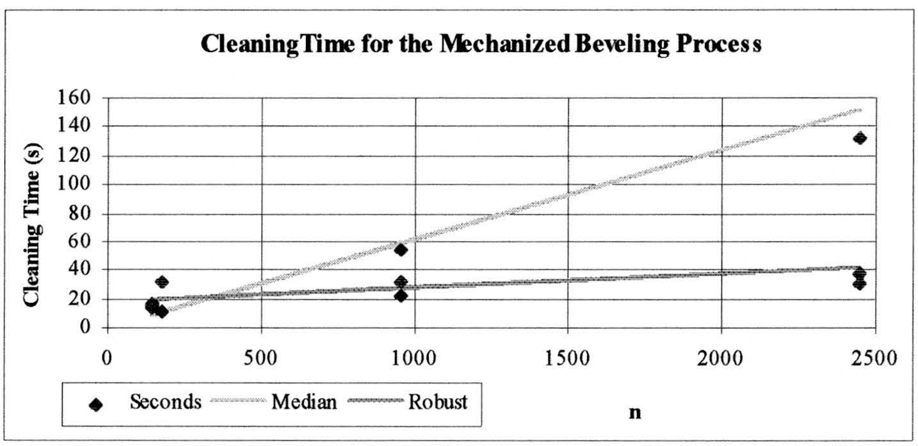

Figure 1.4 Recorded Data Plot of Cleaning Speeds

C.1.5. <u>**Re-Setup Time For Mechanised Bevelling**</u>

Re-Setup Time = 63 seconds. The re-setup time was determined by taking the median of the recorded data. The median value gave the smallest when used to estimate the recorded times.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:45.5	46	64	63	-39.13%	-36.96%
2	00:54.0	54	64	63	-18.52%	-16.67%
3	01:12.0	72	64	63	11.11%	12.50%

4	01:24.0	84	64	63	23.81%	25.00%
				Average Absolute Error	23.14%	22.78%
				Cumulative Error	0.00%	-1.56%
				Standard Deviation	28.49%	28.05%
				Median of Error	-3.70%	-2.08%
				Confidence		
				90%	23.43%	23.07%

Table 1.5 Recorded, Average and Median Re-Setup Times

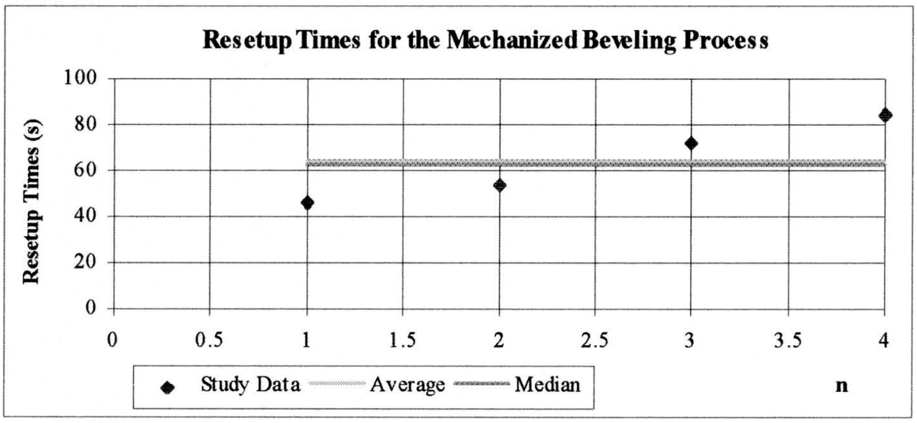

Figure 1.5 Recorded Data Plot of Re-Setup Times

C.2. <u>Measuring and Marking Time</u>

Multiple linear regression was performed on the recorded data along with the average and median speed prediction and adjusted constants of multiple linear regression prediction. Average and median speed estimation makes use of the average and median speed of the recorded data to predict the recorded data while the adjusted constants makes use of numerical methods (Excel Solver) to minimise the average absolute error of prediction. The constants of the multiple linear regression was adjusted until a minimum error was found.

n	Recorded Time	Length (mm)	Number of Lines	Total Length of Lines (mm)	Seconds	Marking Speed (mm/s)
1	00:36.0	900	2	1800	36	50
2	00:37.0	900	2	1800	37	48.64864865
3	07:00.0	2729	3	8187	420	19.49285714
4	06:45.0	2729	3	8187	405	20.21481481
5	01:17.0	2729	1	2729	77	35.44155844
6	01:13.0	2729	1	2729	73	37.38356164

7	02:50.0	3260	2	6520	170	38.35294118
8	04:32.0	2100	2	4200	272	15.44117647
9	01:36.0	1921	2	3842	96	40.02083333
10	00:30.0	1921	1	1921	30	64.03333333
11	01:22.0	65	4	260	82	3.170731707
12	00:55.0	65	4	260	55	4.727272727
13	06:13.0	3803	4	15212	373	40.78284182
14	00:55.0	3803	1	3803	55	69.14545455
15	00:48.0	3803	1	3803	48	79.22916667
16	10:50.0	3803	4	15212	650	23.40307692

Table 2.1 Recorded Data for Measuring and Marking Time

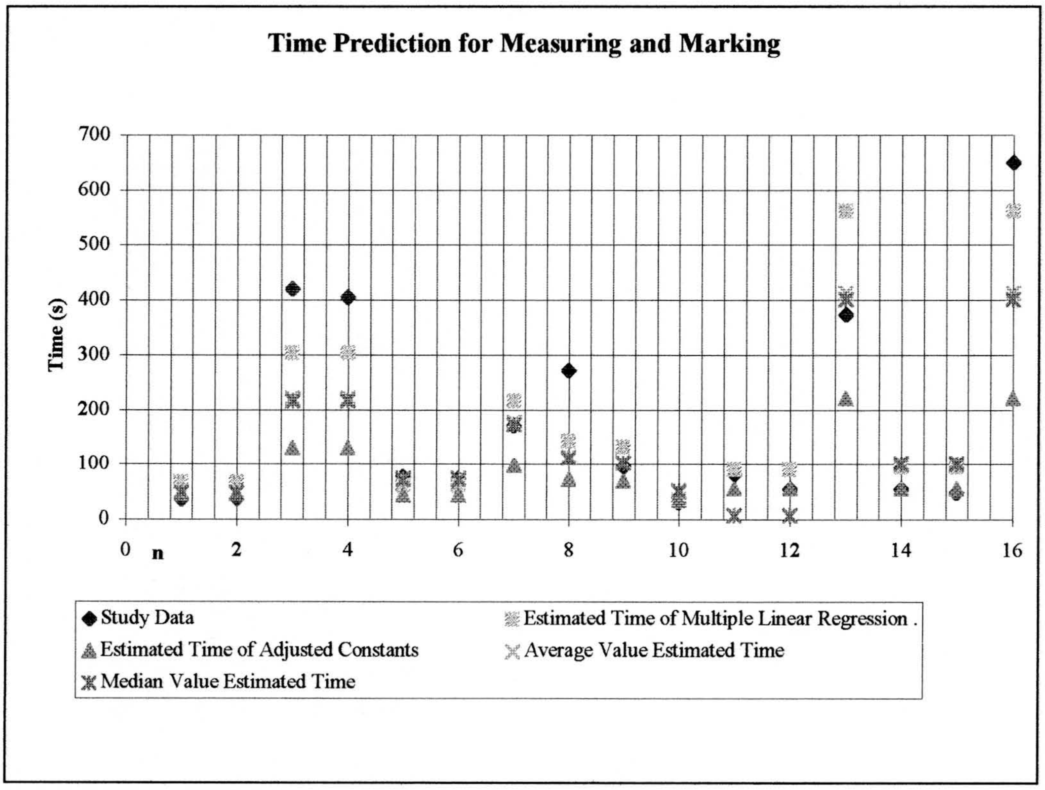

Figure 2.1 Estimated Time Plot

	Multiple Linear Regression	Adjusted Linear Regression	Average Speed	Median Speed
Average Absolute Error	43.25%	36.69%	46.14%	44.72%
Cumulative Error	0.00%	-52.40%	-24.14%	-26.19%
Standard Deviation of Error	46.71%	35.19%	59.89%	58.27%
Median of Error	22.50%	-36.89%	2.78%	0.00%
Confidence				
90%	19.21%	14.47%	24.63%	23.96%

Table 2.2 Summary of Errors of Estimating Formulas

The basic formula for measuring and marking time prediction :

$$T = m_1 \cdot L + m_2 \cdot NL + b$$

Where

L : Total length of lines (mm)
NL : Number of lines

T forced through 0

	m_1	m_2	b
Multiple Linear Regression	0.03153916	35.43654681	-60.62193909
Adjusted Linear Regression	0.01103344	13.0398311	0

Table 2.3 Constant for the Measuring and Marking Equation

C.3. Recorded and Reduced Time Data for Manual Bevelling

C.3.1. Torch Setup Time

Torch Setup Time = 72 seconds. The torch setup time was determined by taking the median of the recorded data. The median value gave the smallest errors when used to predict the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:40.0	40	81.263158	72	103%	80%
2	00:56.0	56	81.263158	72	45%	29%

3	00:31.0	31	81.263158	72	162%	132%
4	01:12.0	72	81.263158	72	13%	0%
5	01:30.0	90	81.263158	72	-10%	-20%
6	02:30.0	150	81.263158	72	-46%	-52%
7	00:42.0	42	81.263158	72	93%	71%
8	01:35.0	95	81.263158	72	-14%	-24%
9	03:15.0	195	81.263158	72	-58%	-63%
10	02:39.0	159	81.263158	72	-49%	-55%
11	01:26.0	86	81.263158	72	-6%	-16%
12	00:21.0	21	81.263158	72	287%	243%
13	00:39.0	39	81.263158	72	108%	85%
14	01:16.0	76	81.263158	72	7%	-5%
15	01:50.0	110	81.263158	72	-26%	-35%
16	00:40.0	40	81.263158	72	103%	80%
17	01:02.0	62	81.263158	72	31%	16%
18	00:40.0	40	81.263158	72	103%	80%
19	02:20.0	140	81.263158	72	-42%	-49%
				Average Absolute Error	68.80%	59.71%
				Cumulative Error	0.00%	-11.40%
				Standard Deviation	88.43%	78.35%
				Median of Error	12.87%	0.00%
				Confidence		
				90%	33.37%	29.57%

Table 3.1 Recorded, Average and Median Torch Setup Times

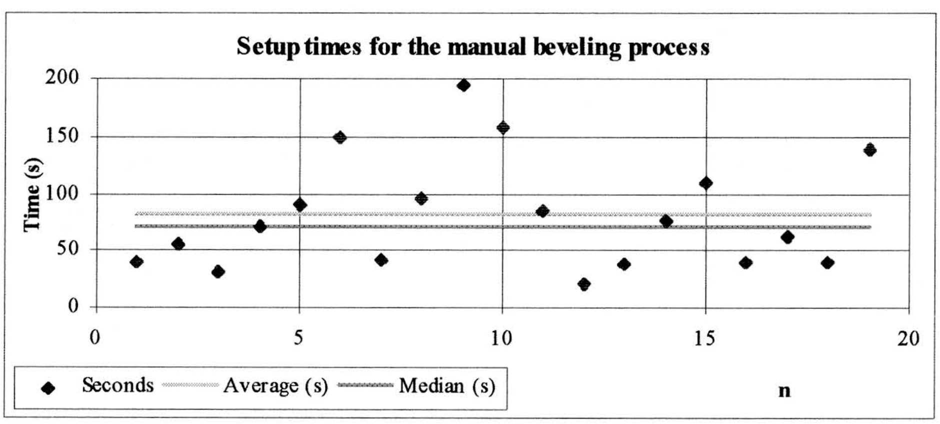

Figure 3.1 Recorded Data Plot of Torch Setup Times

C.3.2. <u>**Torch De-Setup Time for Manual Bevelling**</u>

Torch De-Setup Time = 10 seconds. The torch de-setup time was determined by taking the median of the recorded data. The median value gave the smallest errors when used to estimate the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:08.0	8	11.066667	10	-38%	25%
2	00:12.0	12	11.066667	10	8%	-17%
3	00:12.0	12	11.066667	10	8%	-17%
4	00:09.0	9	11.066667	10	-23%	11%
5	00:07.0	7	11.066667	10	-58%	43%
6	00:08.0	8	11.066667	10	-38%	25%
7	00:13.0	13	11.066667	10	15%	-23%
8	00:11.0	11	11.066667	10	-1%	-9%
9	00:09.0	9	11.066667	10	-23%	11%
10	00:16.0	16	11.066667	10	31%	-38%
11	00:10.0	10	11.066667	10	-11%	0%
12	00:21.0	21	11.066667	10	47%	-52%
13	00:08.0	8	11.066667	10	-38%	25%
14	00:12.0	12	11.066667	10	8%	-17%
15	00:10.0	10	11.066667	10	-11%	0%
				Average Absolute Error	23.82%	20.81%
				Cumulative Error	0.00%	-9.64%
				Standard Deviation	28.81%	26.03%
				Median of Error	-10.67%	0.00%
				Confidence		
				90%	12.2%	11.1%

Table 3.2 Recorded, Average and Median Torch De-Setup Times

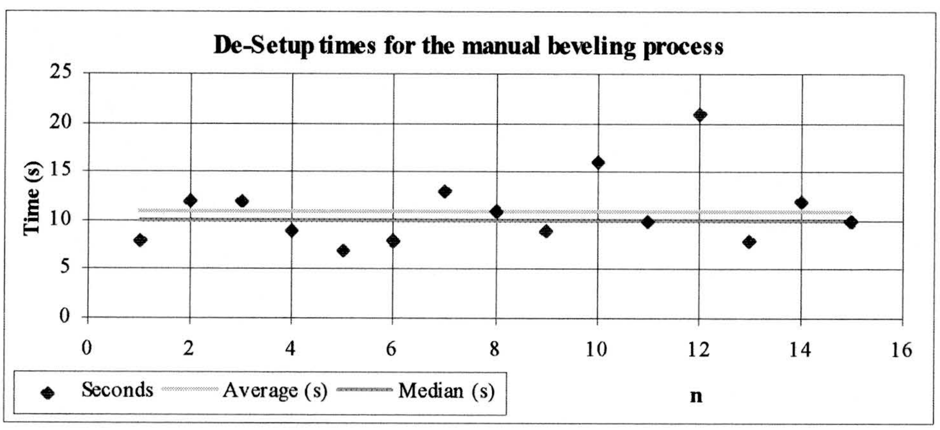

Figure 3.2 Recorded Data Plot of Torch De-Setup Times

C.3.3. Manual Beveling Time

Manual Bevelling Time = 0.256·L+2 s with L in [mm]. The manual bevelling time was determined with robust data analysis of the recorded speed. The robust analysis gave the smallest errors when used to estimate the recorded manual bevelling times.

n	Length (mm)	Seconds	Beveling Speed (mm/min)	Median Speed (mm/min)	Robust Time Estimate (s)	Error of Median	Error of Robust
1	2750	1103	149.59202	229.85572	706.107843	-35%	-36%
2	2750	702	235.04274	229.85572	706.107843	2%	1%
3	2765	795	208.67925	229.85572	709.946078	-9%	-11%
4	1745	416	251.68269	229.85572	448.946078	9%	8%
5	1745	489	214.11043	229.85572	448.946078	-7%	-8%
6	2765	664	249.8494	229.85572	709.946078	9%	7%
7	2750	817	201.95838	229.85572	706.107843	-12%	-14%
8	1745	451	232.15078	229.85572	448.946078	1%	0%
9	2765	715	232.02797	229.85572	709.946078	1%	-1%
10	2765	712	233.00562	229.85572	709.946078	1%	0%
11	1745	376	278.45745	229.85572	448.946078	21%	19%
12	2750	676	244.08284	229.85572	706.107843	6%	4%
13	2750	655	251.9084	229.85572	706.107843	10%	8%
14	1745	460	227.6087	229.85572	448.946078	-1%	-2%
15	2765	698	237.67908	229.85572	709.946078	3%	2%
					Absolute Average Error	8.55%	8.07%
					Cumulative Error	-2.61%	-4.15%
					Standard Deviation	12.71%	12.54%
					Median of Error	1.37%	-0.29%
					Confidence		
					90%	5.40%	5.33%

Table 3.3 Recorded, Median Manual Bevelling Speeds and Robust Estimated Time

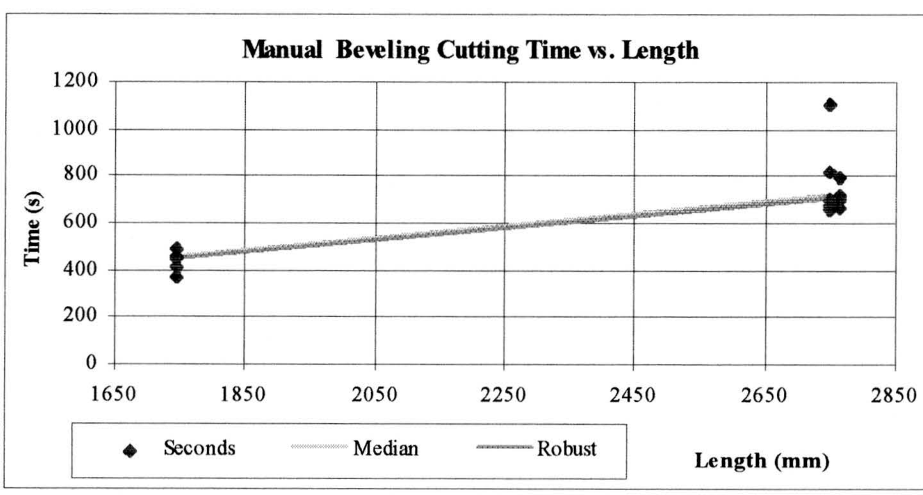

Figure 3.3 Recorded Data Plot of Manual Bevelling Time

C.3.4. Manual Bevelling Cleaning Speed

Manual Bevelling Cleaning Speed = 879 mm per minute. The manual bevel cleaning speed was determined by taking the average of the recorded data. The average value gave the smallest errors when used to predict the recorded data.

n	Recorded Time	Length (mm)	Seconds	Speed (mm/min)	Average (s)	Median (s)	Error of Average	Error of Median
1	04:05.0	1921	245	470.44898	878.757261	828.13688	-46%	-43%
2	01:33.0	1921	93	1239.3548	878.757261	828.13688	41%	50%
3	05:53.0	7260	353	1233.9943	878.757261	828.13688	40%	49%
4	08:46.0	7260	526	828.13688	878.757261	828.13688	-6%	0%
5	03:32.0	3803	212	1076.3208	878.757261	828.13688	22%	30%
6	04:42.0	3803	282	809.14894	878.757261	828.13688	-8%	-2%
7	07:42.0	3803	462	493.8961	878.757261	828.13688	-44%	-40%
						Average Absolute Error	29.70%	30.64%
						Cumulative Error	-6.46%	-0.74%
						Standard Deviation	36.51%	38.74%
						Median of Error	-5.76%	0.00%
						Confidence		
						90.00%	22.70%	24.08%

Table 3.4 Recorded, Average and Median Recorded Cleaning Speeds

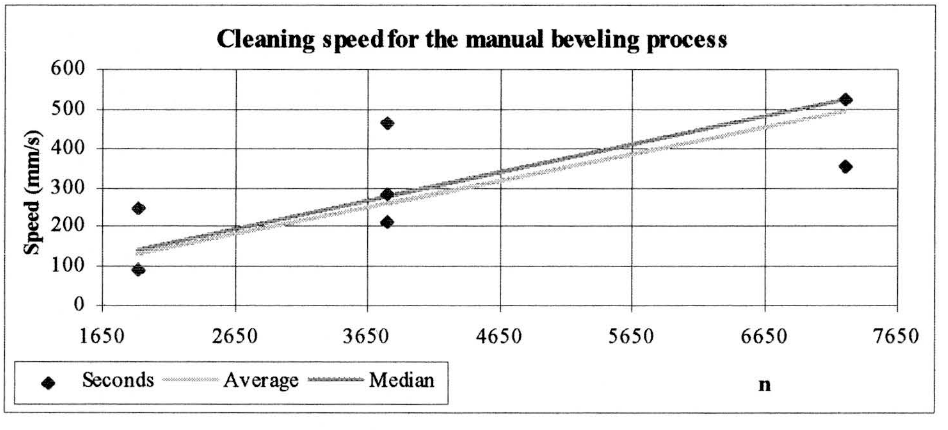

Figure 3.4 Recorded Data Plot for Cleaning Time

C.3.5. Manual Beveling Repositioning Time

Repositioning Time = 21 seconds. The repositioning time was determined by taking the median of the recorded data. The median value gave the smallest errors when used to estimate the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	01:01.0	61	32.984127	21	-46%	-66%
2	01:38.0	98	32.984127	21	-66%	-79%
3	00:25.0	25	32.984127	21	32%	-16%
4	00:24.0	24	32.984127	21	37%	-13%
5	00:17.0	17	32.984127	21	94%	24%
6	00:14.0	14	32.984127	21	136%	50%
7	00:20.0	20	32.984127	21	65%	5%
8	00:26.0	26	32.984127	21	27%	-19%
9	00:23.0	23	32.984127	21	43%	-9%
10	00:29.0	29	32.984127	21	14%	-28%
11	00:30.0	30	32.984127	21	10%	-30%
12	00:31.0	31	32.984127	21	6%	-32%
13	00:20.0	20	32.984127	21	65%	5%
14	00:23.0	23	32.984127	21	43%	-9%
15	00:37.0	37	32.984127	21	-11%	-43%
16	00:12.0	12	32.984127	21	175%	75%
17	00:20.0	20	32.984127	21	65%	5%
18	00:15.0	15	32.984127	21	120%	40%
19	00:18.0	18	32.984127	21	83%	17%
20	00:10.0	10	32.984127	21	230%	110%
21	00:11.0	11	32.984127	21	200%	91%
22	00:15.0	15	32.984127	21	120%	40%
23	00:13.0	13	32.984127	21	154%	62%
24	00:25.0	25	32.984127	21	32%	-16%
25	00:15.0	15	32.984127	21	120%	40%
26	00:36.0	36	32.984127	21	-8%	-42%
27	00:10.0	10	32.984127	21	230%	110%
28	00:30.0	30	32.984127	21	10%	-30%
29	00:18.0	18	32.984127	21	83%	17%
30	00:16.0	16	32.984127	21	106%	31%
31	00:24.0	24	32.984127	21	37%	-13%
32	00:19.0	19	32.984127	21	74%	11%
33	00:47.0	47	32.984127	21	-30%	-55%
34	00:11.0	11	32.984127	21	200%	91%
35	00:38.0	38	32.984127	21	-13%	-45%
36	00:30.0	30	32.984127	21	10%	-30%
37	00:15.0	15	32.984127	21	120%	40%
38	00:24.0	24	32.984127	21	37%	-13%
39	00:17.0	17	32.984127	21	94%	24%
40	00:17.0	17	32.984127	21	94%	24%
41	00:19.0	19	32.984127	21	74%	11%
42	00:24.0	24	32.984127	21	37%	-13%
43	00:16.0	16	32.984127	21	106%	31%
44	00:17.0	17	32.984127	21	94%	24%
45	00:10.0	10	32.984127	21	230%	110%
46	00:24.0	24	32.984127	21	37%	-13%
47	00:15.0	15	32.984127	21	120%	40%
48	00:22.0	22	32.984127	21	50%	-5%
49	00:27.0	27	32.984127	21	22%	-22%
50	00:23.0	23	32.984127	21	43%	-9%
51	00:19.0	19	32.984127	21	74%	11%
52	00:05.0	5	32.984127	21	560%	320%
53	00:20.0	20	32.984127	21	65%	5%

54	00:18.0	18	32.984127	21	83%	17%
55	00:18.0	18	32.984127	21	83%	17%
56	00:12.0	12	32.984127	21	175%	75%
57	00:17.0	17	32.984127	21	94%	24%
58	01:10.0	70	32.984127	21	-53%	-70%
59	00:22.0	22	32.984127	21	50%	-5%
60	00:17.0	17	32.984127	21	94%	24%
61	00:12.0	12	32.984127	21	175%	75%
62	00:20.0	20	32.984127	21	65%	5%
63	00:10.0	10	32.984127	21	230%	110%
64	00:34.0	34	32.984127	21	-3%	-38%
65	00:21.0	21	32.984127	21	57%	0%
66	00:17.0	17	32.984127	21	94%	24%
67	00:51.0	51	32.984127	21	-35%	-59%
68	00:22.0	22	32.984127	21	50%	-5%
69	00:16.0	16	32.984127	21	106%	31%
70	00:11.0	11	32.984127	21	200%	91%
71	00:52.0	52	32.984127	21	-37%	-60%
72	00:42.0	42	32.984127	21	-21%	-50%
73	00:24.0	24	32.984127	21	37%	-13%
74	00:33.0	33	32.984127	21	0%	-36%
75	00:16.0	16	32.984127	21	106%	31%
76	00:38.0	38	32.984127	21	-13%	-45%
77	00:11.0	11	32.984127	21	200%	91%
78	00:20.0	20	32.984127	21	65%	5%
79	00:33.0	33	32.984127	21	0%	-36%
80	00:13.0	13	32.984127	21	154%	62%
81	00:14.0	14	32.984127	21	136%	50%
82	00:31.0	31	32.984127	21	6%	-32%
83	00:10.0	10	32.984127	21	230%	110%
84	00:14.0	14	32.984127	21	136%	50%
85	00:23.0	23	32.984127	21	43%	-9%
86	00:33.0	33	32.984127	21	0%	-36%
87	00:46.0	46	32.984127	21	-28%	-54%
88	00:24.0	24	32.984127	21	37%	-13%
89	00:19.0	19	32.984127	21	74%	11%
90	00:28.0	28	32.984127	21	18%	-25%
91	00:32.0	32	32.984127	21	3%	-34%
92	03:17.0	197	32.984127	21	-83%	-89%
93	03:06.0	186	32.984127	21	-82%	-89%
94	02:46.0	166	32.984127	21	-80%	-87%
95	02:44.0	164	32.984127	21	-80%	-87%
96	02:49.0	169	32.984127	21	-80%	-88%
97	01:21.0	81	32.984127	21	-59%	-74%
98	02:27.0	147	32.984127	21	-78%	-86%
99	02:34.0	154	32.984127	21	-79%	-86%
100	02:49.0	169	32.984127	21	-80%	-88%
101	00:16.0	16	32.984127	21	106%	31%
102	00:12.0	12	32.984127	21	175%	75%
103	00:21.0	21	32.984127	21	57%	0%
104	00:08.0	8	32.984127	21	312%	163%
105	00:14.0	14	32.984127	21	136%	50%
106	00:28.0	28	32.984127	21	18%	-25%
107	00:10.0	10	32.984127	21	230%	110%
108	00:24.0	24	32.984127	21	37%	-13%
109	00:30.0	30	32.984127	21	10%	-30%
110	00:33.0	33	32.984127	21	0%	-36%

111	00:22.0	22	32.984127	21	50%	-5%
112	00:20.0	20	32.984127	21	65%	5%
113	00:06.0	6	32.984127	21	450%	250%
114	00:21.0	21	32.984127	21	57%	0%
115	00:26.0	26	32.984127	21	27%	-19%
116	00:21.0	21	32.984127	21	57%	0%
117	00:13.0	13	32.984127	21	154%	62%
118	00:21.0	21	32.984127	21	57%	0%
119	00:25.0	25	32.984127	21	32%	-16%
120	00:34.0	34	32.984127	21	-3%	-38%
121	00:24.0	24	32.984127	21	37%	-13%
122	00:48.0	48	32.984127	21	-31%	-56%
123	00:17.0	17	32.984127	21	94%	24%
124	00:15.0	15	32.984127	21	120%	40%
125	00:19.0	19	32.984127	21	74%	11%
126	00:26.0	26	32.984127	21	27%	-19%
				Average Absolute Error	85.41%	43.56%
				Cumulative Error	0.00%	-36.33%
				Standard Deviation	97.86%	62.30%
				Median of Error	57.07%	0.00%
				Confidence		
				0.9	14.34%	9.13%

Table 3.5 Recorded, Average and Median Repositioning Times

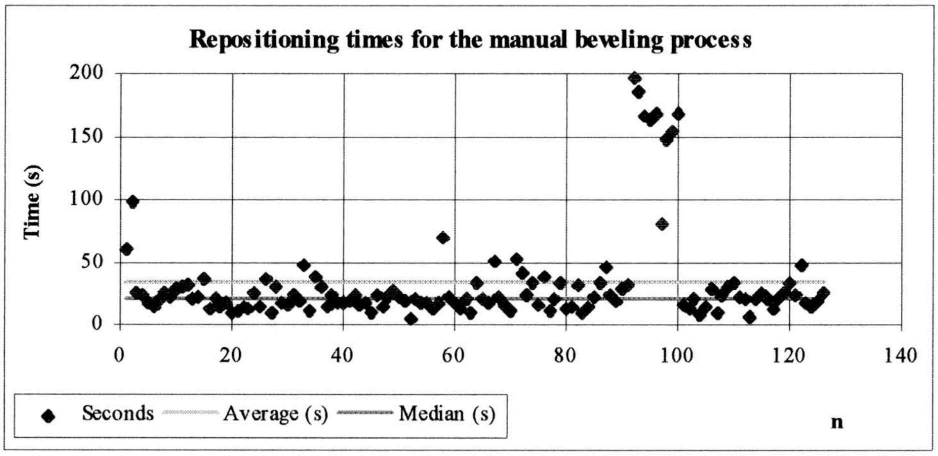

Figure 3.5 Recorded Data Plot for Repositioning Times

C.3.6. <u>Manual Bevelling Repositioning Time without Torch Setup</u>

New Bevel Reposition = 31.5 seconds. The positioning time for a new bevel section without torch setup operation was determined by taking the median of the recorded data. The median value gave the smallest errors when used to predict the recorded data.

n	Recorded Time	Second	Average (s)	Median (s)	Error of Average	Error of Median
1	00:51.0	51	34	31.5	-33%	-38%
2	00:51.0	51	34	31.5	-33%	-38%
3	00:33.0	33	34	31.5	3%	-5%
4	00:29.0	29	34	31.5	17%	9%
5	00:39.0	39	34	31.5	-13%	-19%
6	00:27.0	27	34	31.5	26%	17%
7	00:42.0	42	34	31.5	-19%	-25%
8	00:28.0	28	34	31.5	21%	13%
9	00:10.0	10	34	31.5	240%	215%
10	00:30.0	30	34	31.5	13%	5%
				Average Absolute Error	41.95%	38.30%
				Cumulative Error	0.00%	-7.35%
				Standard Deviation	79.59%	73.74%
				Median of Error	8.18%	0.23%
				Confidence		
				0.9	41.40%	38.36%

Table 3.6 Recorded, Average and Median New Bevell Repositioning Times

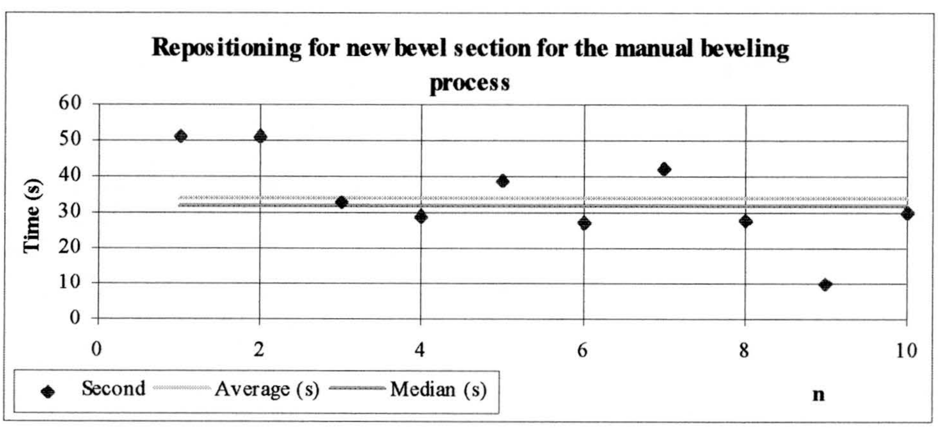

Figure 3.6 Recorded Data Plot of Repositioning for New Section

C.3.7. <u>**Normal Reach For Manual Beveling**</u>

Normal Reach = 260 mm. The normal reach was determined by taking the median of the recorded data.The median value gave the greatest confidence and smallest average absolute error when used to estimate the recorded data.

n	Length	Average (mm)	Median (mm)	Error of Average	Error of Median
1	250	253.9504	260	1.6%	4.0%
2	150	253.9504	260	69.3%	73.3%
3	220	253.9504	260	15.4%	18.2%
4	160	253.9504	260	58.7%	62.5%
5	160	253.9504	260	58.7%	62.5%
6	293	253.9504	260	-13.3%	-11.3%
7	280	253.9504	260	-9.3%	-7.1%
8	110	253.9504	260	130.9%	136.4%
9	262	253.9504	260	-3.1%	-0.8%
10	210	253.9504	260	20.9%	23.8%
11	195	253.9504	260	30.2%	33.3%
12	275	253.9504	260	-7.7%	-5.5%
13	355	253.9504	260	-28.5%	-26.8%
14	330	253.9504	260	-23.0%	-21.2%
15	430	253.9504	260	-40.9%	-39.5%
16	260	253.9504	260	-2.3%	0.0%
17	355	253.9504	260	-28.5%	-26.8%
18	90	253.9504	260	182.2%	188.9%
19	385	253.9504	260	-34.0%	-32.5%
20	160	253.9504	260	58.7%	62.5%
21	155	253.9504	260	63.8%	67.7%
22	345	253.9504	260	-26.4%	-24.6%
23	300	253.9504	260	-15.3%	-13.3%
24	225	253.9504	260	12.9%	15.6%
25	95	253.9504	260	167.3%	173.7%
26	310	253.9504	260	-18.1%	-16.1%
27	235	253.9504	260	8.1%	10.6%
28	225	253.9504	260	12.9%	15.6%
29	270	253.9504	260	-5.9%	-3.7%
30	370	253.9504	260	-31.4%	-29.7%
31	185	253.9504	260	37.3%	40.5%
32	295	253.9504	260	-13.9%	-11.9%
33	295	253.9504	260	-13.9%	-11.9%
34	260	253.9504	260	-2.3%	0.0%
35	300	253.9504	260	-15.3%	-13.3%
36	305	253.9504	260	-16.7%	-14.8%
37	35	253.9504	260	625.6%	642.9%
38	445	253.9504	260	-42.9%	-41.6%
39	180	253.9504	260	41.1%	44.4%
40	140	253.9504	260	81.4%	85.7%
41	115	253.9504	260	120.8%	126.1%
42	25	253.9504	260	915.8%	940.0%
43	260	253.9504	260	-2.3%	0.0%
44	355	253.9504	260	-28.5%	-26.8%
45	180	253.9504	260	41.1%	44.4%
46	205	253.9504	260	23.9%	26.8%
47	330	253.9504	260	-23.0%	-21.2%
48	105	253.9504	260	141.9%	147.6%
49	175	253.9504	260	45.1%	48.6%
50	380	253.9504	260	-33.2%	-31.6%
51	290	253.9504	260	-12.4%	-10.3%
52	375	253.9504	260	-32.3%	-30.7%
53	285	253.9504	260	-10.9%	-8.8%
54	240	253.9504	260	5.8%	8.3%
55	440	253.9504	260	-42.3%	-40.9%

113	75	253.9504	260	238.6%	246.7%
114	50	253.9504	260	407.9%	420.0%
115	135	253.9504	260	88.1%	92.6%
116	315	253.9504	260	-19.4%	-17.5%
117	435	253.9504	260	-41.6%	-40.2%
118	325	253.9504	260	-21.9%	-20.0%
119	250	253.9504	260	1.6%	4.0%
120	430	253.9504	260	-40.9%	-39.5%
121	205	253.9504	260	23.9%	26.8%
122	360	253.9504	260	-29.5%	-27.8%
123	250	253.9504	260	1.6%	4.0%
124	230	253.9504	260	10.4%	13.0%
125	170	253.9504	260	49.4%	52.9%
126	155	253.9504	260	63.8%	67.7%
127	80	253.9504	260	217.4%	225.0%
128	45	253.9504	260	464.3%	477.8%
129	360	253.9504	260	-29.5%	-27.8%
130	135	253.9504	260	88.1%	92.6%
131	105	253.9504	260	141.9%	147.6%
132	375	253.9504	260	-32.3%	-30.7%
133	205	253.9504	260	23.9%	26.8%
134	160	253.9504	260	58.7%	62.5%
135	220	253.9504	260	15.4%	18.2%
136	380	253.9504	260	-33.2%	-31.6%
137	305	253.9504	260	-16.7%	-14.8%
138	240	253.9504	260	5.8%	8.3%
139	230	253.9504	260	10.4%	13.0%
140	350	253.9504	260	-27.4%	-25.7%
141	275	253.9504	260	-7.7%	-5.5%
			Average Absolute Error	64.19%	65.70%
			Cumulative Error	0.00%	2.38%
			Standard Deviation	124.08%	127.04%
			Median of Error	-2.33%	0.00%
			Confidence		
			90%	17.19%	17.60%

Table 3.7 Recorded, Average and Median Data for Normal Reach of Manual Bevelling

56	185	253.9504	260	37.3%	40.5%
57	225	253.9504	260	12.9%	15.6%
58	220	253.9504	260	15.4%	18.2%
59	185	253.9504	260	37.3%	40.5%
60	160	253.9504	260	58.7%	62.5%
61	295	253.9504	260	-13.9%	-11.9%
62	235	253.9504	260	8.1%	10.6%
63	290	253.9504	260	-12.4%	-10.3%
64	440	253.9504	260	-42.3%	-40.9%
65	375	253.9504	260	-32.3%	-30.7%
66	217	253.9504	260	17.0%	19.8%
67	350	253.9504	260	-27.4%	-25.7%
68	225	253.9504	260	12.9%	15.6%
69	355	253.9504	260	-28.5%	-26.8%
70	275	253.9504	260	-7.7%	-5.5%
71	210	253.9504	260	20.9%	23.8%
72	420	253.9504	260	-39.5%	-38.1%
73	90	253.9504	260	182.2%	188.9%
74	110	253.9504	260	130.9%	136.4%
75	420	253.9504	260	-39.5%	-38.1%
76	405	253.9504	260	-37.3%	-35.8%
77	185	253.9504	260	37.3%	40.5%
78	355	253.9504	260	-28.5%	-26.8%
79	135	253.9504	260	88.1%	92.6%
80	240	253.9504	260	5.8%	8.3%
81	435	253.9504	260	-41.6%	-40.2%
82	100	253.9504	260	154.0%	160.0%
83	345	253.9504	260	-26.4%	-24.6%
84	410	253.9504	260	-38.1%	-36.6%
85	95	253.9504	260	167.3%	173.7%
86	325	253.9504	260	-21.9%	-20.0%
87	320	253.9504	260	-20.6%	-18.8%
88	365	253.9504	260	-30.4%	-28.8%
89	80	253.9504	260	217.4%	225.0%
90	105	253.9504	260	141.9%	147.6%
91	370	253.9504	260	-31.4%	-29.7%
92	115	253.9504	260	120.8%	126.1%
93	70	253.9504	260	262.8%	271.4%
94	340	253.9504	260	-25.3%	-23.5%
95	395	253.9504	260	-35.7%	-34.2%
96	350	253.9504	260	-27.4%	-25.7%
97	90	253.9504	260	182.2%	188.9%
98	210	253.9504	260	20.9%	23.8%
99	245	253.9504	260	3.7%	6.1%
100	385	253.9504	260	-34.0%	-32.5%
101	270	253.9504	260	-5.9%	-3.7%
102	490	253.9504	260	-48.2%	-46.9%
103	330	253.9504	260	-23.0%	-21.2%
104	305	253.9504	260	-16.7%	-14.8%
105	340	253.9504	260	-25.3%	-23.5%
106	380	253.9504	260	-33.2%	-31.6%
107	395	253.9504	260	-35.7%	-34.2%
108	310	253.9504	260	-18.1%	-16.1%
109	80	253.9504	260	217.4%	225.0%
110	210	253.9504	260	20.9%	23.8%
111	75	253.9504	260	238.6%	246.7%
112	360	253.9504	260	-29.5%	-27.8%

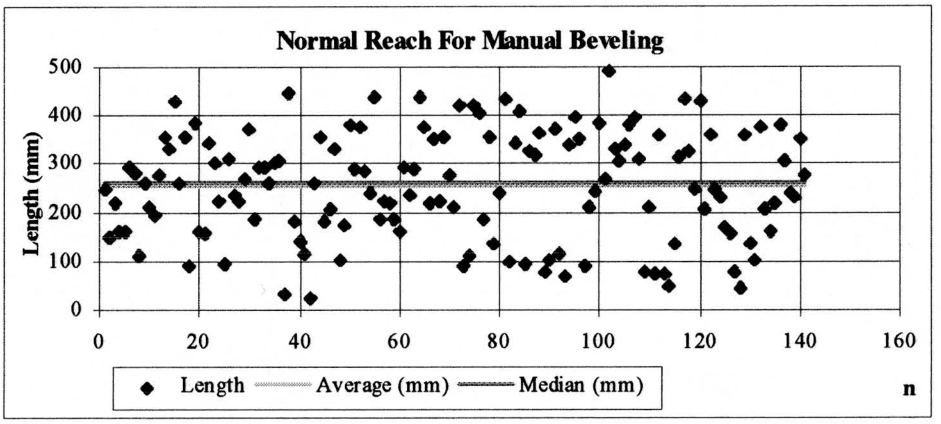

Figure 3.7 Recorded Data Plot of Normal Reach

Appendix D

Plate Bending Data

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D .1. Recorded and Reduced Data for Plate Bending

D .1.1. Bending Press Setup Time

Machine Setup Time = 1464.5 seconds. The bending press setup time was determined by taking the median of the recorded data. The median value gave the smallest errors when used to estimating the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	22:21.4	1341	1468.5	1464.5	10%	9%
2	26:44.0	1604	1468.5	1464.5	-8%	-9%
3	26:26.0	1586	1468.5	1464.5	-7%	-8%
4	22:23.0	1343	1468.5	1464.5	9%	9%
				Average Absolute Error	8.68%	8.65%
				Cumulative Error	0.00%	-0.27%
				Standard Deviation	10.03%	10.00%
				Median of Error	0.97%	0.69%
				Confidence		
				90%	8.25%	8.23%

Table 1.1 Recorded, Average and Median Machine Setup Times

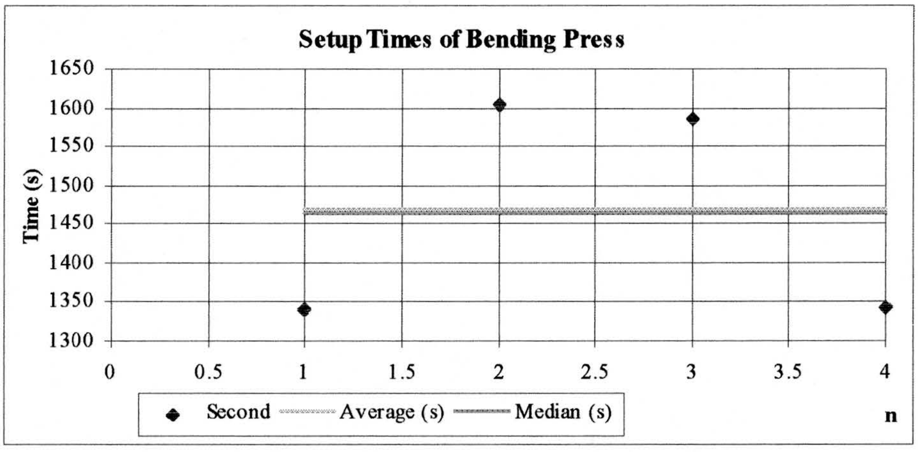

Figure 1.1 Recorded Data Plot of Setup Times

D .1.2. **Material Acquisition Time**

Material Acquisition = 98.5 seconds. The material acquisition times was determined by taking the median of the recorded times. The acquisition was for parts not further than 10 meters from the bending press (region around the press). The median gave the smallest errors when estimating the recorded times.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	03:53.1	233	96.45455	98.5	-59%	-58%
2	01:37.0	97	96.45455	98.5	-1%	2%
3	01:20.0	80	96.45455	98.5	21%	23%
4	01:41.0	101	96.45455	98.5	-5%	-2%
5	02:40.4	160	96.45455	98.5	-40%	-38%
6	01:50.0	110	96.45455	98.5	-12%	-10%
7	00:50.0	50	96.45455	98.5	93%	97%
8	01:10.0	70	96.45455	98.5	38%	41%
9	00:57.0	57	96.45455	98.5	69%	73%
10	00:57.0	57	96.45455	98.5	69%	73%
11	01:10.0	70	96.45455	98.5	38%	41%
12	00:52.0	52	96.45455	98.5	85%	89%
13	01:39.0	99	96.45455	98.5	-3%	-1%
14	00:38.0	38	96.45455	98.5	154%	159%
15	00:30.0	30	96.45455	98.5	222%	228%
16	01:57.0	117	96.45455	98.5	-18%	-16%
17	02:14.0	134	96.45455	98.5	-28%	-26%
18	01:55.0	115	96.45455	98.5	-16%	-14%
19	02:00.0	120	96.45455	98.5	-20%	-18%
20	01:47.0	107	96.45455	98.5	-10%	-8%
21	01:38.0	98	96.45455	98.5	-2%	1%
22	02:07.0	127	96.45455	98.5	-24%	-22%
				Average Absolute Error	58.60%	57.73%
				Cumulative Error	0.00%	2.12%
				Standard Deviation	67.34%	68.77%
				Median of Error	-2.07%	0.00%
				Confidence		
				90%	23.62%	24.12%

Table 1.2 Recorded, Average and Median Material Acquisition Times

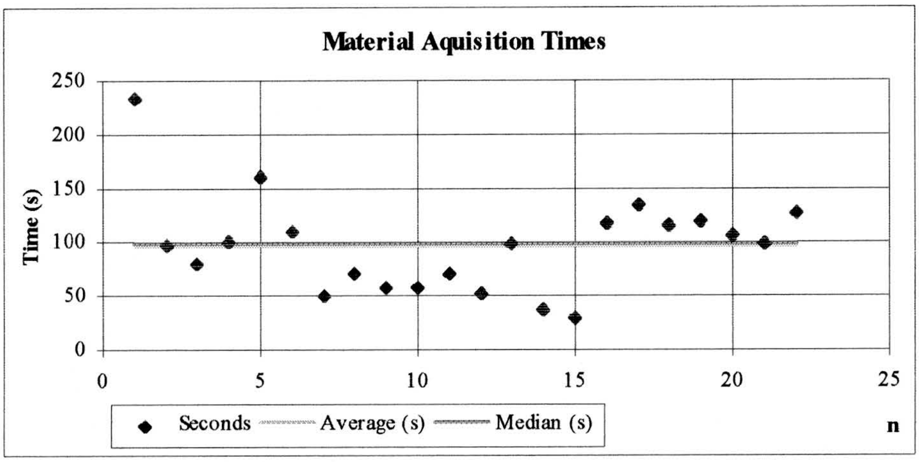

Figure 1.2 Recorded Data Plot of Material Acquisition Times

D .1.3. **Normal Bend Cycle Time**

Normal Bend Cycle Time = 123 seconds. The cycle time for normal bend types was determined by taking the median of the recorded data. The median value predicted the smallest average absolute error and more confidence.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	06:24.0	384	146.8095	123	-61.8%	-68.0%
2	00:59.0	59	146.8095	123	148.8%	108.5%
3	03:46.0	226	146.8095	123	-35.0%	-45.6%
4	04:41.0	281	146.8095	123	-47.8%	-56.2%
5	02:10.0	130	146.8095	123	12.9%	-5.4%
6	02:32.0	152	146.8095	123	-3.4%	-19.1%
7	01:44.0	104	146.8095	123	41.2%	18.3%
8	04:05.0	245	146.8095	123	-40.1%	-49.8%
9	02:32.0	152	146.8095	123	-3.4%	-19.1%
10	02:28.0	148	146.8095	123	-0.8%	-16.9%
11	03:14.0	194	146.8095	123	-24.3%	-36.6%
12	01:22.0	82	146.8095	123	79.0%	50.0%
13	01:47.0	107	146.8095	123	37.2%	15.0%
14	01:32.0	92	146.8095	123	59.6%	33.7%
15	01:29.0	89	146.8095	123	65.0%	38.2%
16	02:57.0	177	146.8095	123	-17.1%	-30.5%
17	00:55.0	55	146.8095	123	166.9%	123.6%
18	02:03.0	123	146.8095	123	19.4%	0.0%
19	01:45.0	105	146.8095	123	39.8%	17.1%
20	01:42.6	103	146.8095	123	42.5%	19.4%

21	01:15.0	75	146.8095	123	95.7%	64.0%
				Average Absolute Error	49.61%	39.76%
				Cumulative Error	0.00%	-16.22%
				Standard Deviation	60.97%	51.08%
				Median of Error	19.36%	0.00%
				Confidence		
				90%	21.88%	18.33%

Table 1.3 Recorded, Average and Median Normal Bend Cycle Times

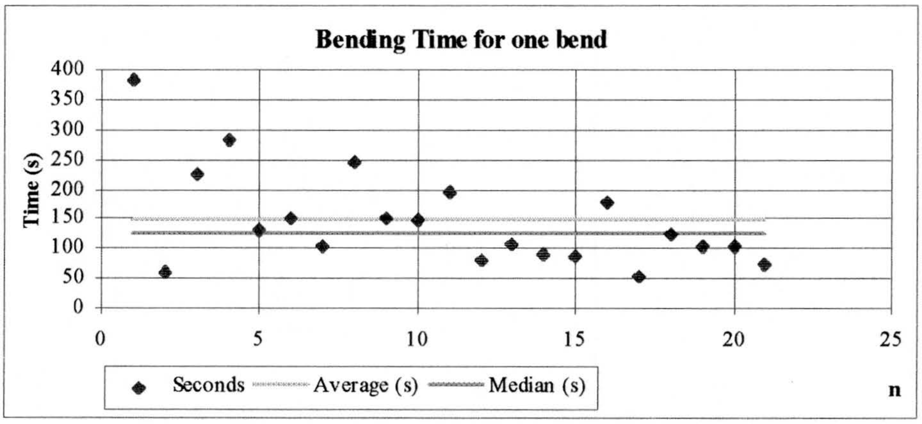

Figure 1.3 Recorded Data Plot of Bend Cycle Time

D .1.4. **Part Preparation Time**

Part Preparation Time = 509 seconds. The part preparation time was taken as the average of the recorded times. The average value gave the smallest errors when estimating the preparation time.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	11:00.0	660	509.7143	513	-23%	-22%
2	07:15.0	435	509.7143	513	17%	18%
3	09:20.0	560	509.7143	513	-9%	-8%
4	06:44.6	405	509.7143	513	26%	27%
5	10:12.0	612	509.7143	513	-17%	-16%
6	06:23.0	383	509.7143	513	33%	34%
7	08:33.4	513	509.7143	513	-1%	0%
				Average Absolute Error	17.89%	17.91%
				Cumulative Error	0.00%	0.64%
				Standard Deviation	21.73%	21.87%
				Median of Error	-0.64%	0.00%
				Confidence		
				90%	13.51%	13.60%

Table 1.4 Recorded, Average and Median Part Preparation Times

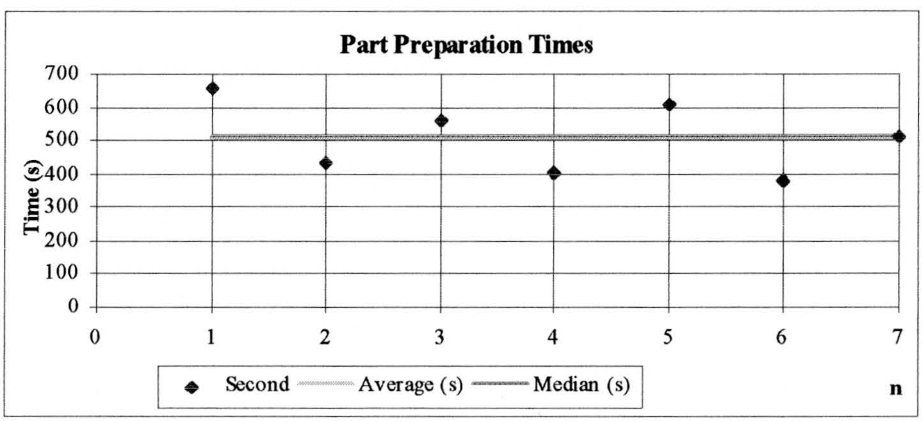

Figure 1.4 Recorded Data Plot of Part Preparation Times

D .1.5. **Back Set Bend Cycle Time**

Back Set Cycle Time = 27 seconds. The back set cycle time was determined by taking the median of the recorded data. The median value gave the smallest average absolute error and the most confidence.

n	Recorded Time	Seconds	Length (mm)	Average (s)	Median (s)	Error of Average	Error of Median
1	00:27.0	27	3848	32.6666667	27	21.0%	0.0%
2	00:27.0	27	3848	32.6666667	27	21.0%	0.0%

3	00:50.0	50	3848	32.6666667	27	-34.7%	-46.0%
4	00:45.0	45	3640	32.6666667	27	-27.4%	-40.0%
5	00:25.0	25	3640	32.6666667	27	30.7%	8.0%
6	00:22.0	22	3640	32.6666667	27	48.5%	22.7%
					Average Absolute Error	30.53%	19.45%
					Cumulative Error	0.00%	-17.35%
					Standard Deviation	33.30%	27.52%
					Median of Error	20.99%	0.00%
					Confidence		
					90%	22.36%	18.48%

Table 1.5 Recorded, Average and Median Back Set Cycle Times

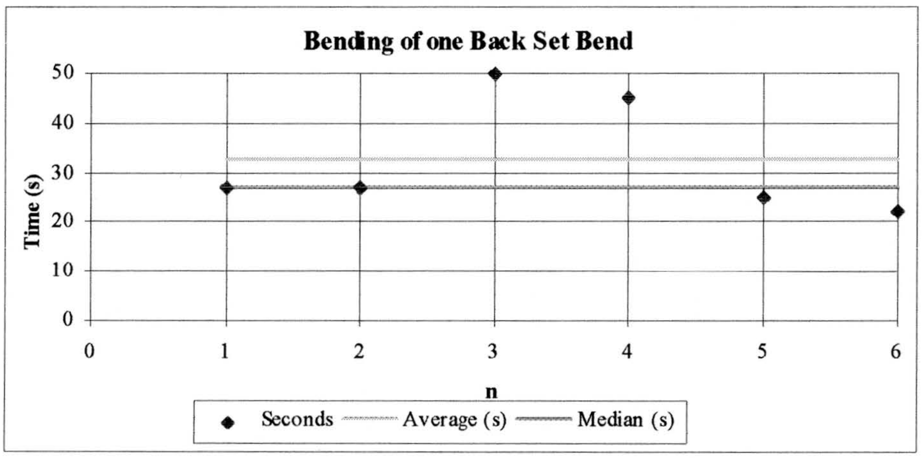

Figure 1.5 Recorded Data Plot of Back Set Bend Cycle Time

D .1.6. **Part Removal Time**

Part Removal Time = 53 seconds. The part removal time was determined by taking the median of the recorded data. The median value gave the smallest errors when used to predict the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	01:15.0	75	57.25	53	-24%	-29%
2	01:29.0	89	57.25	53	-36%	-40%
3	01:37.1	97	57.25	53	-41%	-45%
4	01:05.0	65	57.25	53	-12%	-18%
5	00:50.0	50	57.25	53	15%	6%
6	01:10.0	70	57.25	53	-18%	-24%

7	01:09.0	69	57.25	53	-17%	-23%
8	00:54.0	54	57.25	53	6%	-2%
9	00:31.0	31	57.25	53	85%	71%
10	00:39.0	39	57.25	53	47%	36%
11	00:41.0	41	57.25	53	40%	29%
12	00:33.0	33	57.25	53	73%	61%
13	01:01.0	61	57.25	53	-6%	-13%
14	00:46.0	46	57.25	53	24%	15%
15	00:45.0	45	57.25	53	27%	18%
16	00:46.0	46	57.25	53	24%	15%
17	00:52.0	52	57.25	53	10%	2%
18	01:14.0	74	57.25	53	-23%	-28%
19	00:36.0	36	57.25	53	59%	47%
20	01:31.0	91	57.25	53	-37%	-42%
21	01:06.0	66	57.25	53	-13%	-20%
22	01:09.0	69	57.25	53	-17%	-23%
23	00:35.0	35	57.25	53	64%	51%
24	00:40.0	40	57.25	53	43%	33%
				Average Absolute Error	31.70%	28.88%
				Cumulative Error	0.00%	-7.42%
				Standard Deviation	37.04%	34.29%
				Median of Error	8.06%	0.04%
				Confidence		
				90%	12.44%	11.51%

Table 1.6 Recorded, Average and Median Part Removal Times

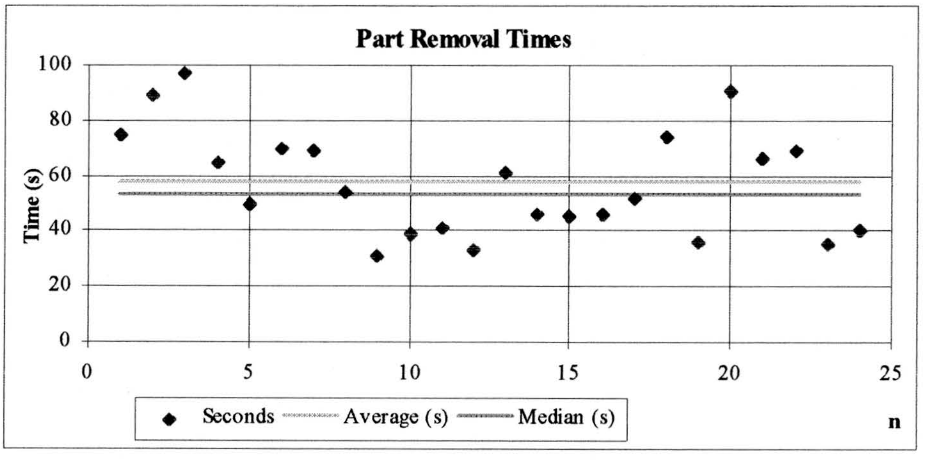

Figure 1.6 Recorded Data Plot of Part Removal Times

D .1.7. **Inching Speed**

Inching Speed = 31.369 mm per minute. The inching speed was determined by dividing the length of the curve that were bent by the recorded times and taking the median value. The median speed gave the smallest errors when used to predict the recorded time.

n	Recorded Time	Seconds	Arc Length of Curve (mm)	Speed (mm/min)	Average (mm/min)	Median (mm/min)	Error of Average Speed	Error of Median Speed
1	17:04.0	1024	763	44.7070313	34.227115	31.369552	31%	43%
2	20:27.6	1228	763	37.2801303	34.227115	31.369552	9%	19%
3	25:15.0	1515	763	30.2178218	34.227115	31.369552	-12%	-4%
4	25:05.0	1505	763	30.4186047	34.227115	31.369552	-11%	-3%
5	25:01.0	1501	763	30.4996669	34.227115	31.369552	-11%	-3%
6	23:40.0	1420	763	32.2394366	34.227115	31.369552	-6%	3%
						Average Absolute Error	13.18%	12.27%
						Cumulative Error	-2.05%	6.87%
						Standard Deviation	16.91%	18.45%
						Median of Error	-8.35%	0.00%
						Confidence		
						90%	11.36%	12.39%

Table 1.7 Recorded, Average and Median Inching Speeds

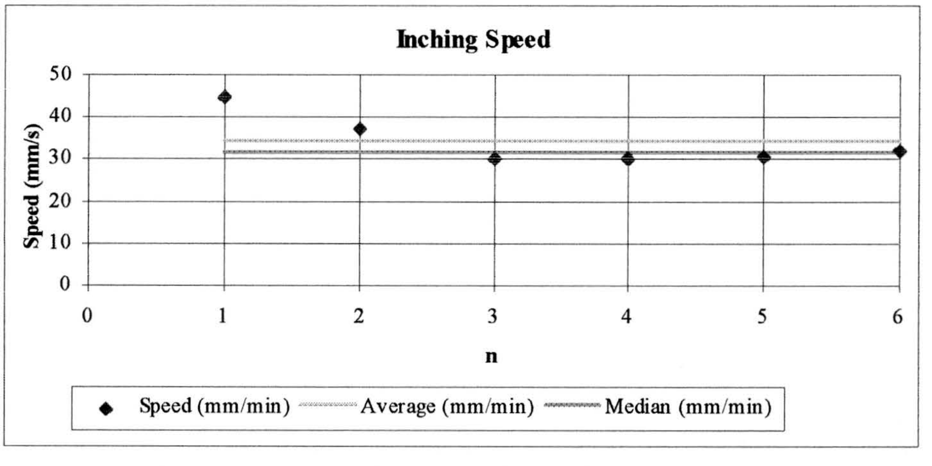

Figure 1.7 Recorded Data Plot of Inching Speed

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E.1. Recorded and Reduced Data for Tack Welding

n	Tack Time	Tack Time With Trimming (s)	Tack Time Without Trimming (s)	Weight of Part (kg)	Total Length of joint (mm)	Number of Joining Lines	Part Curved or Not (1 or 0)	Thickness of Part
1	0:09:43	583	583	146.0	740	1	0	200
2	0:11:29	689	689	48.5	1740	2	0	40
3	0:17:30	1050	1050	63.0	8044	1	0	40
4	0:20:00	1200	1200	63.0	8044	1	0	40
5	0:22:09	1329	1329	63.0	8044	1	0	40
6	0:23:33	1413	1413	63.0	8044	1	0	40
7	0:17:49	1069	1069	1174.6	3334	2	0	50
8	0:26:04	1564	604	351.8	2550	2	0	16
9	0:11:17	677	677	150.8	1975	1	0	16
10	0:08:02	482	482	172.7	1626	1	0	16
11	0:05:25	325	325	87.1	1362	2	0	40
12	0:45:28	2728	1901	182.9	2126	1	1	40
13	0:33:16	1996	1402	301.7	1763	2	1	50
14	0:10:49	649	649	300.7	800	2	1	50
15	0:42:14	2534	1872	99.3	1182	2	1	30
16	0:38:43	2323	1329	99.3	1182	2	1	30
17	0:40:25	2425	1131	99.3	1182	2	1	30
18	0:31:35	1895	826	121.3	2215	2	0	50
19	0:45:42	2742	1835	178.5	1906	2	1	30
20	0:06:34	394	394	40.5	2534	4	0	16
21	0:53:08	3188	3188	596.2	8764	2	0	60
22	0:13:20	800	800	108.9	8090	2	0	30
23	0:25:42	1542	1542	387.7	6660	2	0	50
24	0:13:17	797	797	179.2	6195.888	1	0	30
25	0:13:17	797	797	179.2	6195.888	1	0	30
26	0:28:26	1706	1706	1138.5	6460	3	1	25
27	0:03:20	200	200	44.4	1070	2	0	20
28	0:04:40	280	280	44.4	1070	2	0	20
29	0:03:57	237	237	44.4	1070	2	0	20
30	0:04:05	245	245	44.4	1070	2	0	20
31	0:04:46	286	286	44.4	1070	2	0	20
32	0:04:50	290	290	44.4	1070	2	0	20
33	0:05:17	317	317	49.6	1240	2	0	20
34	0:05:09	309	309	49.6	1240	2	0	20
35	0:05:07	307	307	49.6	1240	2	0	20
36	0:05:40	340	340	49.6	1240	2	0	20
37	0:06:26	386	386	49.6	1240	2	0	20
38	0:05:15	315	315	49.6	1240	2	0	20
39	0:30:40	1840	1840	1072.6	11132	9	1	30
40	0:31:30	1890	1890	1072.6	11132	9	1	30
41	0:19:12	1152	1152	500	1980	4	0	200
42	0:18:28	1108	1108	500	1980	4	0	200
43	0:18:22	1102	1102	500	1980	4	0	200
44	0:18:10	1090	1090	500	1980	4	0	200
45	0:33:46	2026	830	83.2	1880	2	1	60
46	0:47:31	2851	1265	55.6	1480	2	1	60
47	0:24:12	1452	858	88.0	3660	2	1	60
48	12:50.0	770	770	502.3	7158.6	1	0	10

49	14:23.0	863	863	502.3	7158.6	1	0	10
50	28:13.0	1693	1381	121.5	5941.518	3	0	10
51	15:45.0	945	945	155.3	8601	3	0	10
52	22:55.0	1375	1045	191.0	7979	3	0	10
53	03:54.0	234	234	11.9	1596	3	0	16
54	01:29.0	89	89	0.207	127	1	0	12
55	03:53.0	233	233	5.5	489	2	0	16
56	04:17.0	257	257	0.850	412	2	0	16
57	33:40.0	2020	2020	1080.01	5191	1	0	12
58	30:01.0	1801	1801	200.2	9948	2	0	10
59	23:11.0	1391	1391	121.5	5941.518	3	0	10
60	33:17.0	1997	1997	4260	2900	3	0	60
61	09:50.0	4190	4190	13190	2000	2	0	100
62	46:21.0	6381	5253	4100	3970	4	0	60
63	24:00.0	1440	1440	176.2	3000	1	0	50
64	13:57.0	4437	1552	117.4	2150	2	1	50
65	38:40.0	2320	1461	340	2150	1	0	50
66	17:59.0	1079	1079	155.3	8601	3	0	10
	Total	88435	72238	seconds				

Table 1.1 Recorded Data for Tack Welding

E.1.1. <u>**Data Analysis**</u>

The following analysis was done to determine a time estimation equation:

1. Median times were determined for all similar data points. This reduced the data point count used for the formula construction from 66 to 44 data points.
2. A multiple liner regression (MLR) was performed on the new data set with: Part weight (W) [kg], Joining length (L) [mm], Number of joining lines (NL) [], Part curvature (C) [] and Material thickness (T) [mm] as variables. The average absolute error was then determined for the initial data set (66 point data set). The average absolute error for estimating the tack welding time with the formula derived here was 31.2% (see Table 1.2).
3. Each variable were then excluded separately from the MLR and a new MLR analysis (on the 44 point data set) was performed on the remaining data. This was done to determine the variables with the most and least influence on the tack welding time estimation. The average absolute error was then determined for the initial data set (66 point data set). Table 1.2 summarises the errors obtained.
4. The MLR analysis which produced the greatest error decrease, relative to the MLR with all variables, indicate that the variable have no or very little influence on the tack welding time. This showed that the number of joining lines (NL) had no influence on the tack welding time and was therefore excluded from the time

estimation formula (see Table 1.2).

5. The procedure was then repeated without NL as a variable to determine whether the remaining variables were relevant for estimating the tack welding time. Table 1.3 summarises the errors and action taken with the second iteration.

MLR with variables {W,L,NL,C,T}	**MLR with variables {L,NL,C,T}**	**MLR with variables {W,NL,C,T}**	**MLR with variables {W,L,C,T}**	**MLR with variables {W,L,NL,T}**	**MLR with variables {W,L,NL,C}**
31.2%	60.4%	71%	30.1%	46.5%	30.3%
Action taken	Keep W	Keep L	Exclude NL	Keep C	Keep T

Table 1.2 Errors obtained with initial MLR analysis and action taken

MLR with variables {W,L,C,T}	**MLR with variables {L,C,T}**	**MLR with variables {W,C,T}**	**MLR with variables {W,L,T}**	**MLR with variables {W,L,C}**
30.1%	46.8%	51.6%	37.6%	36.8%
Action taken	Keep W	Keep L	Keep C	Keep T

Table 1.3 Errors obtained with second MLR analysis and action taken.

The errors given in Table 1.3 are all bigger than the error of the first column. This therefore indicate that the part weight, length of joining line, part curvature and material thickness have an influence on the tack welding time.

The equation used to estimate the tack welding time is of the form:

Formula for Determining the Basic Assembly Time .

$$T=m_1 \cdot W + m_2 \cdot L + m_3 \cdot C + m_4 \cdot T + b$$

Where

W : Mass of the part (KG)
L : Length of joining lines (mm)
C=1 if part has in plane curvature else C=0
T :Thickness of plate material (mm)

The coefficients for the equation above are summarised in Table 1.4. These coefficients were the coefficients obtained with the MLR analysis that had part weight, length of joining line, part curvature and material thickness as variables.

Coefficient	m_1	m_2	m_3	m_4	b
Value	0.325	0.157	567	4.783	0
Units	$\frac{s}{kg}$	$\frac{s}{mm}$	[s]	$\frac{s}{mm}$	[s]

Table 1.4 Multiple Linear Regression Coefficients

The basic tack welding time estimation with the coefficients listed in Table 1.4 gave the following errors. An average absolute error of 30% and a cumulative error of -2% for the recorded data. The standard deviation of the error was 36.23%. Statistical analysis shows, with a confidence of 90%, that the error would be less than -1%±7% for individual component tack welding.

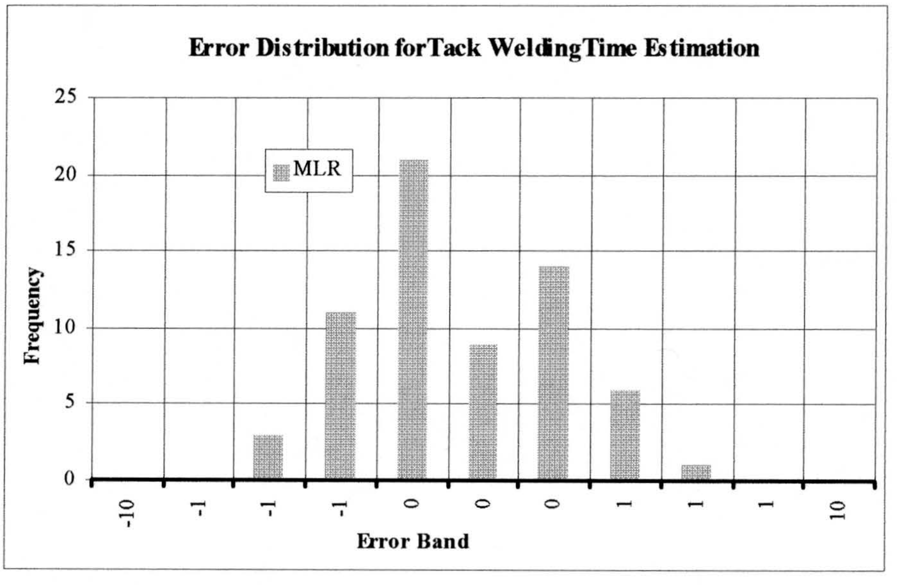

Figure 1.1 Error Distribution for Estimating Tacking Time

E.1.2. Time Correction Factor for Trimming

Time Correction For Trimming = 0.2737*(Basic Assembling Time). The trimming correction factor was determined by assuming random distributed trimming requirements and dividing the total trimming time of the recorded data by the total basic assembling time.

Recorded trimming time of parts that had fit-up problems and the correction factor for trimming which was determined by dividing the total trimming time by the predicted basic assembly time.

n	Total Tacking Time	Seconds	Part Curved or Not (1 or 0)	Add Time Required for Trimming	Seconds	Minimum Tacking Time (s)	Ratio of Trimming/ Tacking
1	0:26	1564	0	16:00.0	960	604	159%
2	0:45	2728	1	13:47.0	827	1901	44%
3	0:33	1996	1	09:54.0	594	1402	42%
4	0:42	2534	1	11:02.0	662	1872	35%
5	0:38	2323	1	16:34.0	994	1329	75%
6	0:40	2425	1	21:34.0	1294	1131	114%
7	0:31	1895	0	17:49.0	1069	826	129%
8	0:45	2742	1	15:07.0	907	1835	49%
9	0:33	2026	1	19:56.0	1196	830	144%
10	0:47	2851	1	26:26.0	1586	1265	125%
11	0:24	1452	1	09:54.0	594	858	69%
14	1:46	6381	0	18:48.0	1128	1653	68%
15	1:13	4437	1	48:05.0	2885	1552	186%
16	0:38	2320	0	14:19.0	859	1461	59%
12	0:28	1693	0	05:12.0	312	1381	23%
13	0:22	1375	0	05:30.0	330	1045	32%
				Total Trimming Time (s)	16197	Basic Tacking Time (Measured) (s)	72238
				Trimming Correction Factor as a Ratio	0.273746		

Table 1.5 Recorded Trimming Time of Parts and the Trimming/Tacking Ratio

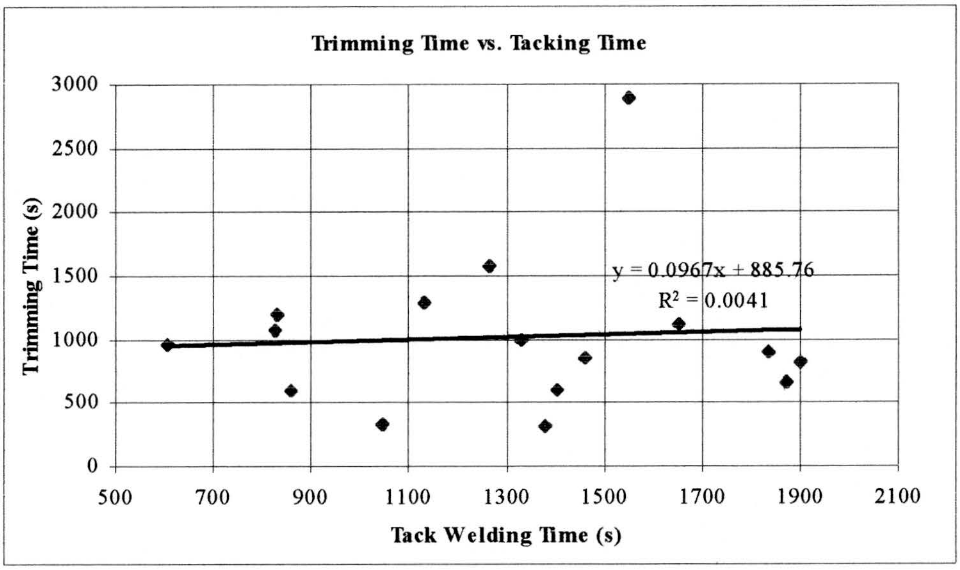

Figure 1.2 Trimming Time vs. Tack Welding Time

E.2. Recorded and Reduced Handling Time Data

E.2.1. Part Connecting Time for Crane Handling

Part Connecting Time = 37 seconds. The part connecting times was determined by taking the median of the recorded data. This median value gave the smallest overall errors when used to estimate the recorded times.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:22.0	22	48.92	37	122%	68%
2	00:16.0	16	48.92	37	206%	131%
3	00:53.0	53	48.92	37	-8%	-30%
4	00:08.0	8	48.92	37	512%	363%
5	00:37.0	37	48.92	37	32%	0%
6	01:50.0	110	48.92	37	-56%	-66%
7	00:31.0	31	48.92	37	58%	19%
8	00:38.0	38	48.92	37	29%	-3%
9	00:52.0	52	48.92	37	-6%	-29%
10	00:23.0	23	48.92	37	113%	61%
11	00:48.0	48	48.92	37	2%	-23%
12	00:33.0	33	48.92	37	48%	12%
13	01:02.0	62	48.92	37	-21%	-40%
14	00:31.0	31	48.92	37	58%	19%
15	01:33.0	93	48.92	37	-47%	-60%
16	02:57.0	177	48.92	37	-72%	-79%
17	01:32.0	92	48.92	37	-47%	-60%
18	00:27.0	27	48.92	37	81%	37%
19	00:13.0	13	48.92	37	276%	185%

20	00:11.0	11	48.92	37	345%	236%
21	00:48.0	48	48.92	37	2%	-23%
22	01:03.0	63	48.92	37	-22%	-41%
23	00:25.0	25	48.92	37	96%	48%
24	01:38.0	98	48.92	37	-50%	-62%
25	00:12.0	12	48.92	37	308%	208%
				Average Absolute Error	104.63%	76.19%
				Cumulative Error	0.00%	-24.37%
				Standard Deviation	145.94%	110.38%
				Median of Error	32.22%	0.00%
				Confidence		
				90%	48.01%	36.31%

Table 2.1 Recorded, Average and Median Part Connecting Times

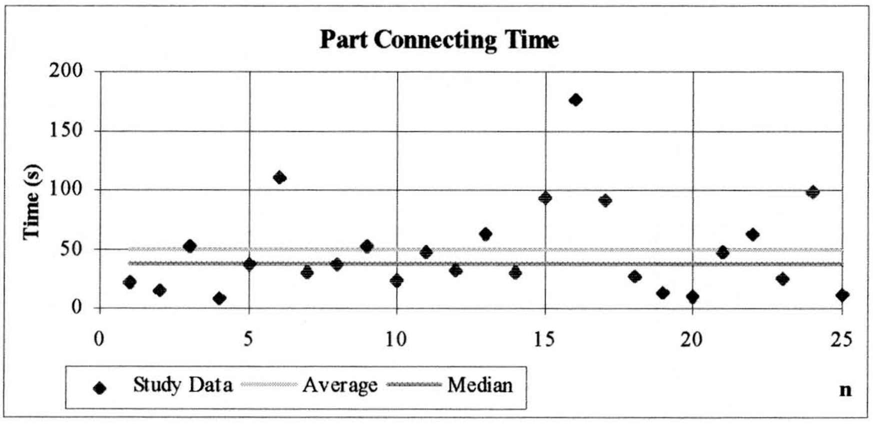

Figure 2.1 Recorded Data Plot of Part Connecting Times

E.2.2. **Part Disconnecting Time for Crane Handling.**

Disconnecting Time = 15 seconds. The part disconnecting times was determined by taking the median of the recorded data. The median gave the smallest errors when used to predict the recorded values.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:15.0	15	20.82609	15	39%	0%
2	00:04.0	4	20.82609	15	421%	275%
3	00:03.0	3	20.82609	115	594%	400%
4	00:17.0	17	20.82609	15	23%	-12%
5	00:35.0	35	20.82609	15	-40%	-57%
6	00:48.0	48	20.82609	15	-57%	-69%

7	00:05.0	5	20.82609	15	317%	200%
8	00:14.0	14	20.82609	15	49%	7%
9	00:41.0	41	20.82609	15	-49%	-63%
10	00:22.0	22	20.82609	15	-5%	-32%
11	00:25.0	25	20.82609	15	-17%	-40%
12	00:41.0	41	20.82609	15	-49%	-63%
13	00:06.0	6	20.82609	15	247%	150%
14	01:06.0	66	20.82609	15	-68%	-77%
15	00:24.0	24	20.82609	15	-13%	-38%
16	00:38.0	38	20.82609	15	-45%	-61%
17	00:13.0	13	20.82609	15	60%	15%
18	00:04.0	4	20.82609	15	421%	275%
19	00:07.0	7	20.82609	15	198%	114%
20	00:15.0	15	20.82609	15	39%	0%
21	00:18.0	18	20.82609	15	16%	-17%
22	00:15.0	15	20.82609	15	39%	0%
23	00:03.0	3	20.82609	15	594%	400%
				Average Absolute Error	147.78%	102.83%
				Cumulative Error	0.00%	-27.97%
				Standard Deviation	209.89%	151.17%
				Median of Error	38.84%	0.00%
				Confidence		
				90%	71.99%	51.85%

Table 2.2 Recorded, Average and Median Part Disconnecting Times

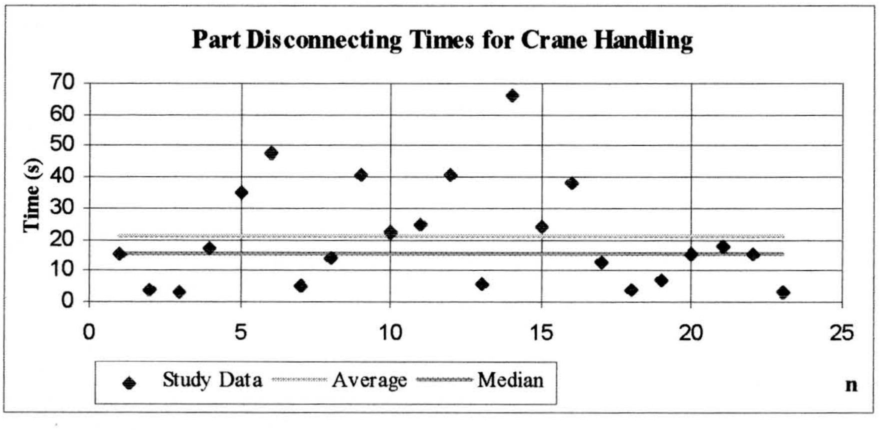

Figure 2.2 Recorded Data Plot of Part Disconnecting Times

E.2.3. Moving Time of Crane With Part

Part Moving Time = $2.2 \cdot D + 42$ seconds with D in [m] and $2 \le D \le 71$.

The part moving speed was determined with robust data analysis of the recorded data. The robust equation gave the smallest errors when used to predict the recorded times.

n	Recorded Time	Distance (m)	Seconds	Speed (m/s)	Median (m/s)	Robust Time Estimate (s)	Error of Median	Error of Robust
1	00:47.0	10	47	0.212766	0.195023	63.52707	9%	35%
2	01:19.0	15	79	0.189873	0.195023	74.286543	-3%	-6%
3	02:17.0	43	137	0.313869	0.195023	134.53959	61%	-2%
4	00:42.0	2	42	0.047619	0.195023	46.311914	-76%	10%
5	00:30.0	3	30	0.1	0.195023	48.463809	-49%	62%
6	02:42.0	71	162	0.438272	0.195023	194.79264	125%	20%
7	01:07.0	16	67	0.238806	0.195023	76.438438	22%	14%
8	00:50.0	6	50	0.12	0.195023	54.919492	-38%	10%
9	00:57.0	3	57	0.052632	0.195023	48.463809	-73%	-15%
10	02:32.0	44	152	0.289474	0.195023	136.69148	48%	-10%
11	01:37.0	37	97	0.381443	0.195023	121.62822	96%	25%
12	00:59.0	29	59	0.491525	0.195023	104.41307	152%	77%
13	02:03.0	23	123	0.186992	0.195023	91.501699	-4%	-26%
14	01:34.0	5	94	0.053191	0.195023	52.767598	-73%	-44%
15	03:49.0	12	229	0.052402	0.195023	67.830859	-73%	-70%
16	01:42.0	5	102	0.04902	0.195023	52.767598	-75%	-48%
17	01:19.0	8	79	0.101266	0.195023	59.223281	-48%	-25%
18	00:52.0	3.5	52	0.067308	0.195023	49.539756	-65%	-5%
19	00:35.0	8.5	35	0.242857	0.195023	60.299229	25%	72%
20	03:17.0	59	197	0.299492	0.195023	168.9699	54%	-14%
21	00:12.0	2	12	0.166667	0.195023	46.311914	-15%	286%
						Average Absolute Error	56.32%	41.74%
						Cumulative Error	9.18%	-7.80%
						Standard Deviation	69.25%	72.37%
						Median of Error	-4.12%	-1.80%
						Confidence		
						90%	24.85%	25.97%

Table 2.3 Recorded, Average and Median Part Moving Speeds

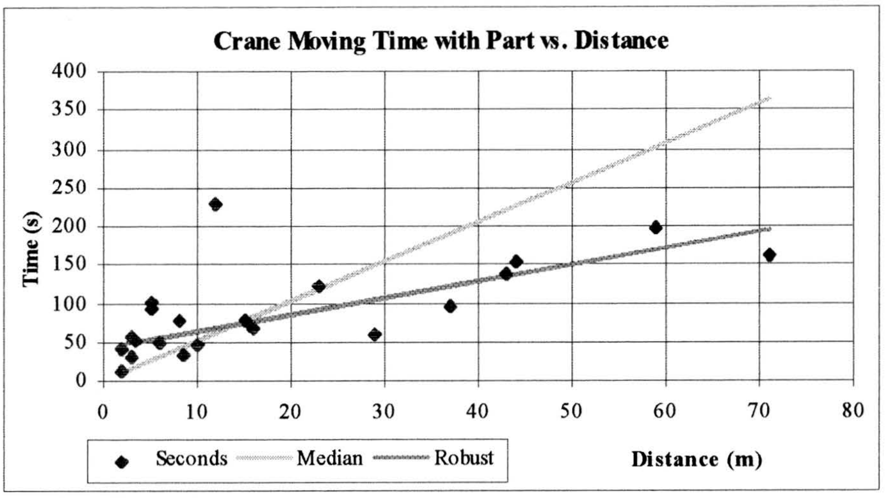

Figure 2.3 Part moving times

E.2.4. Crane Moving Time without Part

Crane Moving Time = $1.3 \cdot D+20$ seconds with D in [m] and $2 \leq D \leq 63$

The crane moving time equation was determined with robust data analysis of the recorded data. The robust method gave the smallest overall errors when used to predict the recorded times.

n	Recorded Time	Distance (m)	Seconds	Speed (m/s)	Median (m/s)	Robust Estimate (s)	Error of Median	Error of Robust
1	00:14.0	3	14	0.214286	0.276923	24.392137	-23%	74%
2	00:26.0	3.5	26	0.134615	0.276923	25.056601	-51%	-4%
3	00:45.0	18	45	0.4	0.276923	44.326046	44%	-1%
4	00:25.0	8	25	0.32	0.276923	31.036774	16%	24%
5	00:09.0	4	9	0.444444	0.276923	25.721065	60%	186%
6	00:42.0	6	42	0.142857	0.276923	28.378919	-48%	-32%
7	01:32.0	7.5	92	0.081522	0.276923	30.37231	-71%	-67%
8	00:34.0	7	34	0.205882	0.276923	29.707846	-26%	-13%
9	00:30.0	7	30	0.233333	0.276923	29.707846	-16%	-1%
10	01:34.0	21	94	0.223404	0.276923	48.312828	-19%	-49%
11	00:58.0	9	58	0.155172	0.276923	32.365701	-44%	-44%
12	01:05.0	18	65	0.276923	0.276923	44.326046	0%	-32%
13	00:25.0	10	25	0.4	0.276923	33.694628	44%	35%
14	00:25.0	2	25	0.08	0.276923	23.06321	-71%	-8%
15	01:01.0	31	61	0.508197	0.276923	61.6021	84%	1%
16	00:26.0	2	26	0.076923	0.276923	23.06321	-72%	-11%
17	00:52.0	5	52	0.096154	0.276923	27.049992	-65%	-48%
18	00:26.0	12	26	0.461538	0.276923	36.352483	67%	40%
19	01:21.0	43	81	0.530864	0.276923	77.549227	92%	-4%
20	00:27.0	16	27	0.592593	0.276923	41.668191	114%	54%

21	02:20.0	63	140	0.45	0.276923	104.12777	63%	-26%
22	00:27.0	16	27	0.592593	0.276923	41.668191	114%	54%
23	00:44.0	7	44	0.159091	0.276923	29.707846	-43%	-32%
24	00:48.0	32	48	0.666667	0.276923	62.931027	141%	31%
25	00:15.0	6	15	0.4	0.276923	28.378919	44%	89%
26	01:11.0	37	71	0.521127	0.276923	69.575664	88%	-2%
27	00:43.0	25	43	0.581395	0.276923	53.628537	110%	25%
28	01:16.0	46	76	0.605263	0.276923	81.536009	119%	7%
29	00:19.0	4	19	0.210526	0.276923	25.721065	-24%	35%
30	01:00.0	3	60	0.05	0.276923	24.392137	-82%	-59%
31	03:15.0	35	195	0.179487	0.276923	66.917809	-35%	-66%
						Average Absolute Error	60.94%	37.27%
						Cumulative Error	14.79%	-18.10%
						Standard Deviation	69.16%	52.43%
						Median of Error	44.44%	-2.01%
						Confidence		
						90%	20.43%	15.49%

Table 2.4 Recorded, Average and Median Crane Moving Speed Without Part

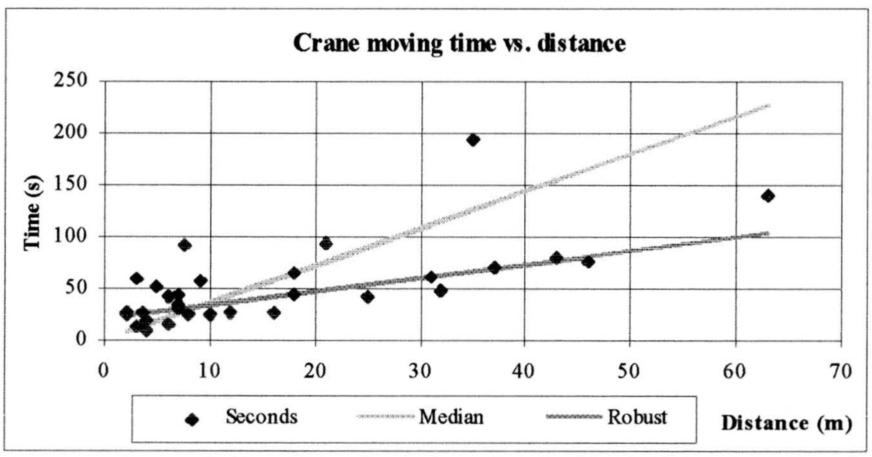

Figure 2.4 Crane Moving Times

E.2.5. **Part Turn Time**

Part Turn Time = 196 seconds. The part turn time was determined by taking the median of the recorded data. He median produced the smallest errors when used to estimate the part turn time.

n	Recorded Time (s)	Average (s)	Median (s)	Error of Average	Error of Median
1	79	239	196	203%	148%
2	196	239	196	22%	0%

3	347	239	196	-31%	-44%
4	127	239	196	89%	54%
5	77	239	196	211%	155%
6	61	239	196	293%	221%
7	580	239	196	-59%	-66%
8	393	239	196	-39%	-50%
9	385	239	196	-38%	-49%
10	92	239	196	161%	113%
11	300	239	196	-20%	-35%
			Average Absolute Error	106%	85%
			Cumulative Error	0%	-18%
			Standard Deviation	125%	102%
			Median of Error	22%	0%
			Confidence		
			90%	62%	27%

Table 2.5 Recorded Data, Average and Median Values for Part Turn Times

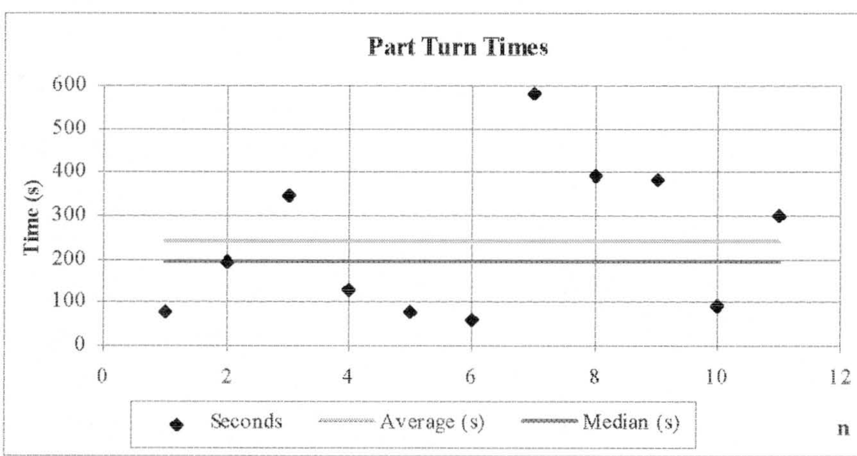

Figure 2.5 Recorded Data Plot for Part Turn Times

Appendix F

Welding and Back Gouging Data

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F.1. **Recorded and Reduced Data for Welding**

F.1.1. **Wire Diameter Properties**

F.1.1.1. *Area Covered with 1.2 mm Flux Core Wire*

Cross Sectional Area Covered With 1.2mm Wire = 21.33 square mm. The cross sectional area covered with one pass of welding was determined by taking the median of the recorded data. The median value gave the smallest errors when used to estimate the recorded data.

n	Area (mm^2)	Weld Size (Fillet)	Weld Runs	Area Per Run (mm^2/run)	Error of Average	Error of Median
1	50	10	3	16.66666667	-33%	-33%
2	128	16	6	21.33333333	0%	0%
3	242	22	11	22	0%	0%
4	312.5	25	15	20.83333333	0%	0%
5	450	30	17	26.47058824	24%	24%
6	50	10	3	16.66666667	-33%	-33%
7	128	16	6	21.33333333	0%	0%
8	242	22	10	24.2	10%	10%
				Average Absolute Error	12.52%	12.52%
				Cumulative Error	4.23%	4.23%
				Standard Deviation	19.78%	19.78%
				Median of Error	0%	0%
				Confidence		
				90%	11.50%	11.50%

Average (mm^2/run)	21.18799
Median (mm^2/run)	21.333333

Table 1.1 Recorded, Average and Median Data for Area Covered with 1.2mm FCAW Wire

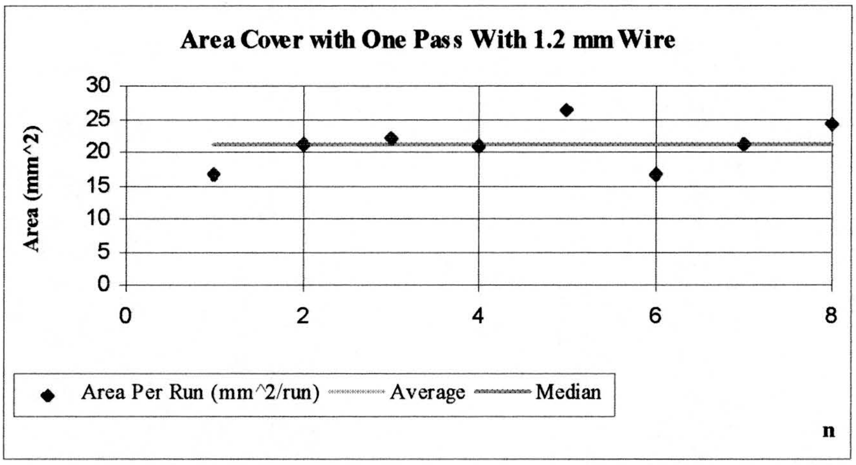

Figure 1.1 Recorded Data Plot of Area Covered with One Weld Pass

F .1.1.2. *Area Covered with 1.6 mm Flux Core Wire*

Cross Sectional Area Covered with 1.6 mm Wire = 25 square mm. The cross sectional area covered with a single pass run was determined by taking the median of the recorded data. The median gave the smallest errors when used to estimate the recorded data.

n	Area (mm^2)	Weld Size (Fillet)	Weld Runs	Area Per Run (mm^2/run)	Error of Average	Error of Median
1	32	8	1	32	0%	0%
2	50	10	1	50	100%	100%
3	50	10	2	25	0%	0%
4	72	12	3	24	0%	0%
2	72	12	3	24	0%	0%
3	72	12	3	24	0%	0%
4	98	14	3	32.66666667	33%	33%
5	128	16	6	21.33333333	-17%	-17%
3	128	16	5	25.6	0%	0%
4	128	16	4	32	25%	25%
5	200	20	8	25	-13%	0%
6	312.5	25	11	28.40909091	0%	18%
4	312.5	-	15	20.83333333	-27%	-13%
5	450	30	17	26.47058824	-6%	6%
6	1800	60	80	22.5	-19%	-10%

Average Absolute Error	15.92%	14.83%
Cumulative Error	-11.73%	-3.09%
Standard Deviation	30.31%	28.42%
Median of Error	0.00%	0.00%
Confidence		
90%	12.87%	12.07%

Average (mm^2/run)	27.587534
Median (mm^2/run)	25

Table 1.2 Recorded, Average and Median Data for Area Covered with 1.6mm FCAW Wire

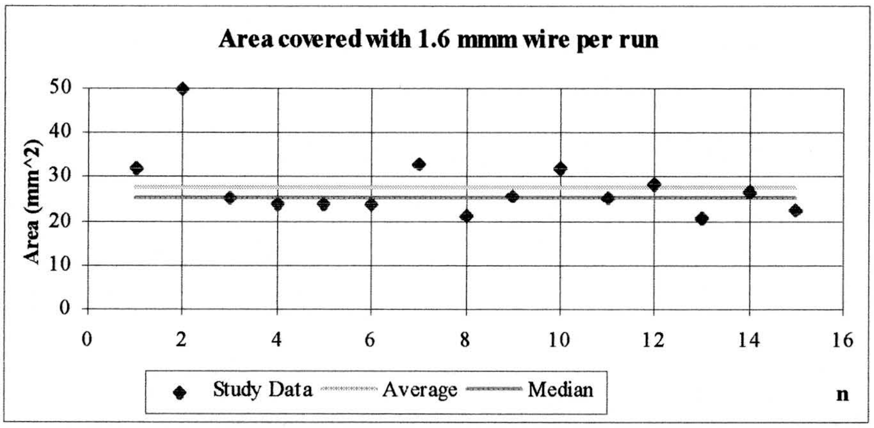

Figure 1.2 Recorded Data Plot of area Covered with One Weld Pass

F .1.1.3. *Area Covered with 2.4 mm Flux Core Wire*

Cross Sectional Area Covered With 2.4 mm Wire = 35.36 square mm. The cross sectional area covered with one pass was determined by taking the average of the recorded data. The average value gave the smallest errors when used to predict the recorded data.

n	Area (mm^2)	Weld Size (Fillet)	Weld Runs	Area Per Run (mm^2/run)	Error of Average	Error of Median
1	128	16	4	32	0%	0%
2	32	8	1	32	0%	0%
3	50	10	1	50	0%	100%
4	50	10	2	25	-50%	0%
5	50	10	1	50	0%	100%
6	84.5	13	2	42.25	0%	50%
7	84.5	13	3	28.16666667	-33%	0%
8	112.5	15	3	37.5	0%	0%
9	128	16	3	42.66666667	33%	33%
10	128	16	4	32	0%	0%
11	180.5	19	5	36.1	0%	20%
12	180.5	19	7	25.78571429	-29%	-14%
13	242	22	7	34.57142857	0%	0%
14	242	22	8	30.25	-13%	-13%
15	312.5	25	8	39.0625	13%	25%
16	312.5	25	12	26.04166667	-25%	-17%
17	312.5	25	6	52.08333333	50%	67%
18	512	32	13	39.38461538	8%	23%
19	512	32	10	51.2	40%	60%
20	722	38	24	30.08333333	-17%	-8%
21	722	38	22	32.81818182	-9%	0%
22	1058	46	27	39.18518519	11%	19%
23	1058	46	35	30.22857143	-14%	-9%
24	1300.5	51	36	36.125	3%	11%
25	1300.5	51	46	28.27173913	-20%	-13%
26	162	18	6	27	-17%	-17%
27	200	20	8	25	-25%	-25%

Average Absolute Error	15.11%	23.07%
Cumulative Error	-5.59%	3.62%
Standard Deviation	21.75%	33.87%
Median of Error	0.00%	0.00%
Confidence		
90%	6.88%	10.72%

Average (mm^2/run)	35.362022
Median (mm^2/run)	32.818182

Table 1.3 Recorded, Average and Median Data for Area Covered With 2.4mm FCAW Wire

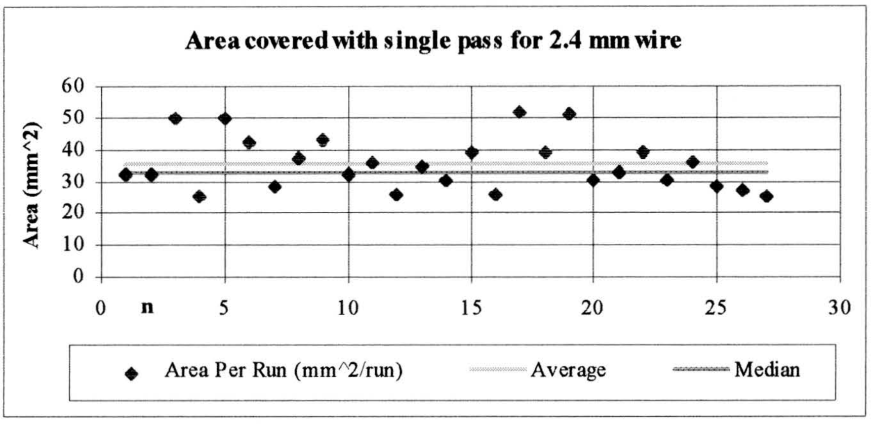

Figure 1.3 Recorded Data Plot of Area Covered with One Weld Pass

F .1.2. **Weld Run Fettling Speed**

Fettling Speed Per Run = 877.7 mm per minute. The fettling speed of one weld run was determined by taking the median of the recorded data. The median gave the smallest cumulative error when used to estimate the recorded data.

n	Recorded Time	Seconds	Length (mm)	Speed (mm/min)	Average (mm/min)	Median (mm/min)	Error of Average	Error of Median
1	03:15.0	195	1685	518.46154	1097.242	877.745902	-53%	-41%
2	01:13.0	73	1685	1384.9315	1097.242	877.745902	26%	58%
3	02:41.0	161	1685	627.95031	1097.242	877.745902	-43%	-28%
4	00:58.0	58	1685	1743.1034	1097.242	877.745902	59%	99%
5	01:25.0	85	1685	1189.4118	1097.242	877.745902	8%	36%
6	01:04.0	64	1685	1579.6875	1097.242	877.745902	44%	80%
7	01:20.0	80	1685	1263.75	1097.242	877.745902	15%	44%
8	01:11.0	71	1685	1423.9437	1097.242	877.745902	30%	62%
9	00:46.0	46	885	1154.3478	1097.242	877.745902	5%	32%
10	00:27.0	27	885	1966.6667	1097.242	877.745902	79%	124%
11	01:01.0	61	885	870.4918	1097.242	877.745902	-21%	-1%
12	01:09.0	69	885	769.56522	1097.242	877.745902	-30%	-12%
13	01:09.0	69	885	769.56522	1097.242	877.745902	-30%	-12%
14	02:18.0	138	885	384.78261	1097.242	877.745902	-65%	-56%
15	00:37.0	37	885	1435.1351	1097.242	877.745902	31%	64%
16	01:11.0	71	885	747.88732	1097.242	877.745902	-32%	-15%
17	01:02.0	62	885	856.45161	1097.242	877.745902	-22%	-2%
18	01:32.0	92	885	577.17391	1097.242	877.745902	-47%	-34%
19	01:14.0	74	885	717.56757	1097.242	877.745902	-35%	-18%
20	00:16.0	16	885	3318.75	1097.242	877.745902	202%	278%
21	00:55.0	55	885	965.45455	1097.242	877.745902	-12%	10%
22	01:00.0	60	885	885	1097.242	877.745902	-19%	1%

23	01:12.0	72	885	737.5	1097.242	877.745902	-33%	-16%
24	01:59.0	119	885	446.21849	1097.242	877.745902	-59%	-49%
						Average Absolute Error	41.68%	48.83%
						Cumulative Error	-18.52%	1.85%
						Standard Deviation	57.71%	72.15%
						Median of Error	-20.00%	0.00%
						Confidence		
						90%	19.38%	24.22%

Table 1.4 Recorded, Average and Median Data for Weld Run Fettling Speed

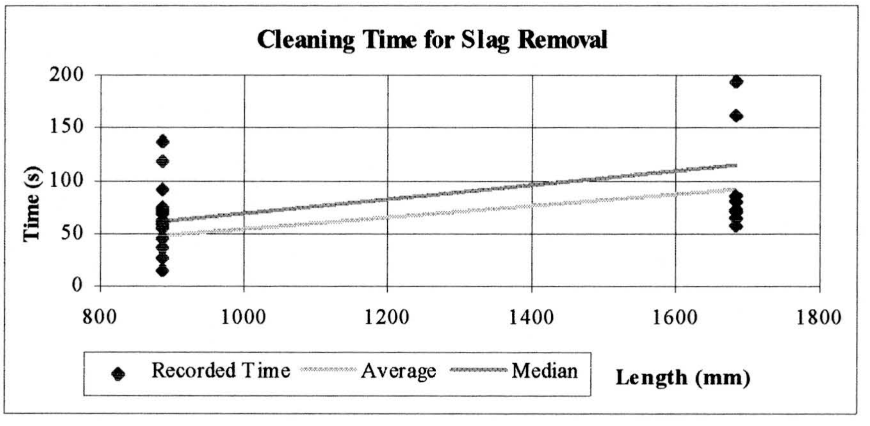

Figure 1.4 Cleaning Time vs. Weld Length

F .1.3. <u>Welding Operator Setup Time</u>

Setup Time = 10.5 seconds. The welding operator setup time was determined by taking the median of the recorded data. The median value gave the smallest errors when estimating the recorded data.

n	Recorded Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:08.8	9	13.026316	10.5	45%	17%
2	00:33.0	33	13.026316	10.5	-61%	-68%
3	00:35.0	35	13.026316	10.5	-63%	-70%
4	00:07.0	7	13.026316	10.5	86%	50%
5	00:15.0	15	13.026316	10.5	-13%	-30%
6	00:22.3	22	13.026316	10.5	-41%	-52%
7	00:31.0	31	13.026316	10.5	-58%	-66%
8	00:05.0	5	13.026316	10.5	161%	110%
9	00:12.0	12	13.026316	10.5	9%	-13%
10	00:11.0	11	13.026316	10.5	18%	-5%
11	00:18.0	18	13.026316	10.5	-28%	-42%

12	00:04.5	5	13.026316	10.5	161%	110%
13	00:08.0	8	13.026316	10.5	63%	31%
14	00:10.0	10	13.026316	10.5	30%	5%
15	00:13.0	13	13.026316	10.5	0%	-19%
16	00:07.0	7	13.026316	10.5	86%	50%
17	00:18.0	18	13.026316	10.5	-28%	-42%
18	00:21.0	21	13.026316	10.5	-38%	-50%
19	00:17.0	17	13.026316	10.5	-23%	-38%
20	00:05.0	5	13.026316	10.5	161%	110%
21	00:05.0	5	13.026316	10.5	161%	110%
22	00:12.9	13	13.026316	10.5	0%	-19%
23	00:32.0	32	13.026316	10.5	-59%	-67%
24	00:09.0	9	13.026316	10.5	45%	17%
25	00:22.0	22	13.026316	10.5	-41%	-52%
26	00:06.0	6	13.026316	10.5	117%	75%
27	00:07.0	7	13.026316	10.5	86%	50%
28	00:08.0	8	13.026316	10.5	63%	31%
29	00:04.0	4	13.026316	10.5	226%	163%
30	00:17.0	17	13.026316	10.5	-23%	-38%
31	00:11.0	11	13.026316	10.5	18%	-5%
32	00:08.0	8	13.026316	10.5	63%	31%
33	00:06.0	6	13.026316	10.5	117%	75%
34	00:11.0	11	13.026316	10.5	18%	-5%
35	00:10.0	10	13.026316	10.5	30%	5%
36	00:07.0	7	13.026316	10.5	86%	50%
37	00:05.0	5	13.026316	10.5	161%	110%
38	00:12.0	12	13.026316	10.5	9%	-13%
				Average of Absolute Error	65.62%	49.80%
				Cumulative Error	0.00%	-19.39%
				Standard Deviation	76.24%	61.46%
				Median of Error	24.34%	0.23%
				Confidence		
				90%	20.34%	16.40%

Table 1.5 Recorded, Average and Median Data for Weld Operator Setup Time

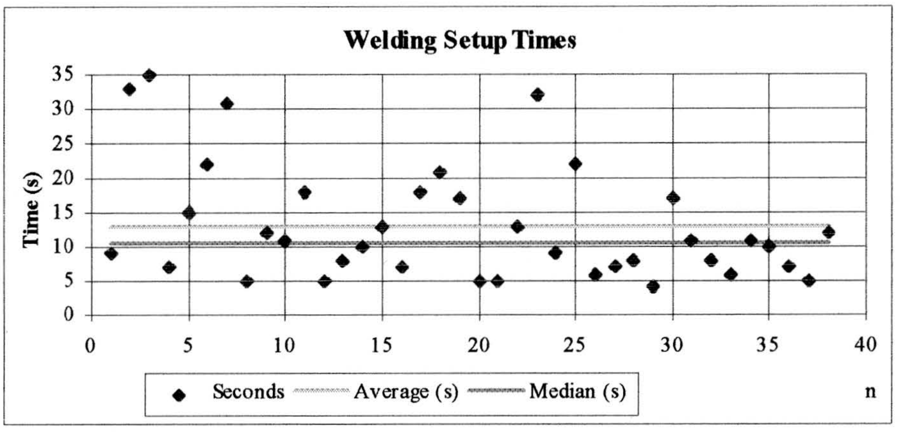

Figure 1.5 Recorded Data Plot of Welding Setup Times

F .1.4. Welding Operator De-Setup Time

De-Setup Time = 5 seconds. The de-setup time was determined by taking the median of the recorded data. The median gave the smallest errors when used to estimate the recorded data.

n	Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	00:06.0	6	4.8684211	5	-19%	-17%
2	00:04.0	4	4.8684211	5	22%	25%
3	00:05.0	5	4.8684211	5	-3%	0%
4	00:07.0	7	4.8684211	5	-30%	-29%
5	00:03.0	3	4.8684211	5	62%	67%
6	00:03.7	4	4.8684211	5	22%	25%
7	00:03.0	3	4.8684211	5	62%	67%
8	00:05.0	5	4.8684211	5	-3%	0%
9	00:03.0	3	4.8684211	5	62%	67%
10	00:03.0	3	4.8684211	5	62%	67%
11	00:06.0	6	4.8684211	5	-19%	-17%
12	00:04.0	4	4.8684211	5	22%	25%
13	00:07.0	7	4.8684211	5	-30%	-29%
14	00:07.0	7	4.8684211	5	-30%	-29%
15	00:05.0	5	4.8684211	5	-3%	0%
16	00:07.0	7	4.8684211	5	-30%	-29%
17	00:10.0	10	4.8684211	5	-51%	-50%
18	00:07.0	7	4.8684211	5	-30%	-29%
19	00:03.0	3	4.8684211	5	62%	67%
20	00:04.0	4	4.8684211	5	22%	25%
21	00:02.0	2	4.8684211	5	143%	150%
22	00:08.0	8	4.8684211	5	-39%	-38%
23	00:04.0	4	4.8684211	5	22%	25%
24	00:02.0	2	4.8684211	5	143%	150%
25	00:03.0	3	4.8684211	5	62%	67%
26	00:04.0	4	4.8684211	5	22%	25%

27	00:05.0	5	4.8684211	5	-3%	0%
28	00:06.0	6	4.8684211	5	-19%	-17%
29	00:03.0	3	4.8684211	5	62%	67%
30	00:08.0	8	4.8684211	5	-39%	-38%
31	00:04.0	4	4.8684211	5	22%	25%
32	00:05.0	5	4.8684211	5	-3%	0%
33	00:07.0	7	4.8684211	5	-30%	-29%
34	00:06.0	6	4.8684211	5	-19%	-17%
35	00:03.0	3	4.8684211	5	62%	67%
36	00:02.0	2	4.8684211	5	143%	150%
37	00:05.0	5	4.8684211	5	-3%	0%
38	00:05.0	5	4.8684211	5	-3%	0%
				Average Absolute Error	39.12%	40.04%
				Cumulative Error	0.00%	2.70%
				Standard Deviation	51.15%	52.53%
				Median of Error	-2.63%	0.00%
				Confidence		
				90%	13.65%	1.46%

Table 1.6 Recorded, Average and Median Data for Operator De-Setup Times

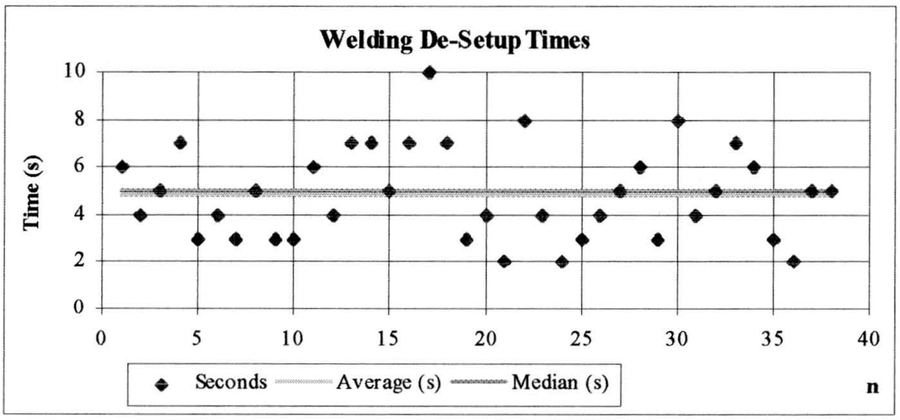

Figure 1.6 Recorded Data Plot of Welding De-Setup Times

F .1.5. <u>Welding Operator Normal Reach</u>

Normal Reach of Operator = 832.5 mm. The normal reach of the welding operator was determined by taking the median of the recorded data. The median value gave the smallest errors when used to estimate the recorded data.

n	Length (mm)	Average (mm)	Median (mm)	Error of Average	Error of Median
1	1050	902.9911	832.5	-14%	-21%
2	1350	902.9911	832.5	-33%	-38%
3	1670	902.9911	832.5	-46%	-50%

4	635	902.9911	832.5	42%	31%
5	1510	902.9911	832.5	-40%	-45%
6	1350	902.9911	832.5	-33%	-38%
7	1070	902.9911	832.5	-16%	-22%
8	1020	902.9911	832.5	-11%	-18%
9	1020	902.9911	832.5	-11%	-18%
10	990	902.9911	832.5	-9%	-16%
11	1270	902.9911	832.5	-29%	-34%
12	900	902.9911	832.5	0%	-8%
13	900	902.9911	832.5	0%	-8%
14	2120	902.9911	832.5	-57%	-61%
15	1100	902.9911	832.5	-18%	-24%
16	1280	902.9911	832.5	-29%	-35%
17	1110	902.9911	832.5	-19%	-25%
18	1800	902.9911	832.5	-50%	-54%
19	790	902.9911	832.5	14%	5%
20	860	902.9911	832.5	5%	-3%
21	1030	902.9911	832.5	-12%	-19%
22	1270	902.9911	832.5	-29%	-34%
23	1370	902.9911	832.5	-34%	-39%
24	1300	902.9911	832.5	-31%	-36%
25	610	902.9911	832.5	48%	36%
26	710	902.9911	832.5	27%	17%
27	1410	902.9911	832.5	-36%	-41%
28	1500	902.9911	832.5	-40%	-45%
29	1580	902.9911	832.5	-43%	-47%
30	1580	902.9911	832.5	-43%	-47%
31	1230	902.9911	832.5	-27%	-32%
32	1270	902.9911	832.5	-29%	-34%
33	1300	902.9911	832.5	-31%	-36%
34	770	902.9911	832.5	17%	8%
35	1000	902.9911	832.5	-10%	-17%
36	1970	902.9911	832.5	-54%	-58%
37	830	902.9911	832.5	9%	0%
38	670	902.9911	832.5	35%	24%
39	800	902.9911	832.5	13%	4%
40	500	902.9911	832.5	81%	67%
41	640	902.9911	832.5	41%	30%
42	780	902.9911	832.5	16%	7%
43	790	902.9911	832.5	14%	5%
44	1000	902.9911	832.5	-10%	-17%
45	930	902.9911	832.5	-3%	-10%
46	900	902.9911	832.5	0%	-8%
47	600	902.9911	832.5	50%	39%
48	540	902.9911	832.5	67%	54%
49	400	902.9911	832.5	126%	108%
50	570	902.9911	832.5	58%	46%
51	730	902.9911	832.5	24%	14%
52	790	902.9911	832.5	14%	5%
53	390	902.9911	832.5	132%	113%
54	575	902.9911	832.5	57%	45%
55	420	902.9911	832.5	115%	98%
56	700	902.9911	832.5	29%	19%
57	660	902.9911	832.5	37%	26%
58	480	902.9911	832.5	88%	73%
59	500	902.9911	832.5	81%	67%
60	790	902.9911	832.5	14%	5%
61	830	902.9911	832.5	9%	0%
62	1000	902.9911	832.5	-10%	-17%
63	430	902.9911	832.5	110%	94%
64	520	902.9911	832.5	74%	60%
65	560	902.9911	832.5	61%	49%
66	740	902.9911	832.5	22%	13%
67	680	902.9911	832.5	33%	22%

68	1000	902.9911	832.5	-10%	-17%
69	1000	902.9911	832.5	-10%	-17%
70	950	902.9911	832.5	-5%	-12%
71	620	902.9911	832.5	46%	34%
72	1050	902.9911	832.5	-14%	-21%
73	730	902.9911	832.5	24%	14%
74	740	902.9911	832.5	22%	13%
75	1060	902.9911	832.5	-15%	-21%
76	710	902.9911	832.5	27%	17%
77	900	902.9911	832.5	0%	-8%
78	1000	902.9911	832.5	-10%	-17%
79	950	902.9911	832.5	-5%	-12%
80	1270	902.9911	832.5	-29%	-34%
81	960	902.9911	832.5	-6%	-13%
82	565	902.9911	832.5	60%	47%
83	540	902.9911	832.5	67%	54%
84	770	902.9911	832.5	17%	8%
85	660	902.9911	832.5	37%	26%
86	835	902.9911	832.5	8%	0%
87	800	902.9911	832.5	13%	4%
88	930	902.9911	832.5	-3%	-10%
89	1090	902.9911	832.5	-17%	-24%
90	1000	902.9911	832.5	-10%	-17%
91	600	902.9911	832.5	50%	39%
92	560	902.9911	832.5	61%	49%
93	660	902.9911	832.5	37%	26%
94	780	902.9911	832.5	16%	7%
95	610	902.9911	832.5	48%	36%
96	550	902.9911	832.5	64%	51%
97	560	902.9911	832.5	61%	49%
98	960	902.9911	832.5	-6%	-13%
99	670	902.9911	832.5	35%	24%
100	550	902.9911	832.5	64%	51%
101	480	902.9911	832.5	88%	73%
102	1000	902.9911	832.5	-10%	-17%
103	550	902.9911	832.5	64%	51%
104	1080	902.9911	832.5	-16%	-23%
105	1035	902.9911	832.5	-13%	-20%
106	1420	902.9911	832.5	-36%	-41%
107	740	902.9911	832.5	22%	13%
108	1090	902.9911	832.5	-17%	-24%
109	900	902.9911	832.5	0%	-8%
110	560	902.9911	832.5	61%	49%
111	600	902.9911	832.5	50%	39%
112	610	902.9911	832.5	48%	36%
			Average Absolute Error	33.41%	30.56%
			Cumulative Error	0.00%	-7.81%
			Standard Deviation	40.99%	37.79%
			Median of Error	8.47%	0.00%
			Confidence		
			90%	6.37%	5.87%

Table 1.7 Recorded, Average and Median Data of Normal Reach of Operator

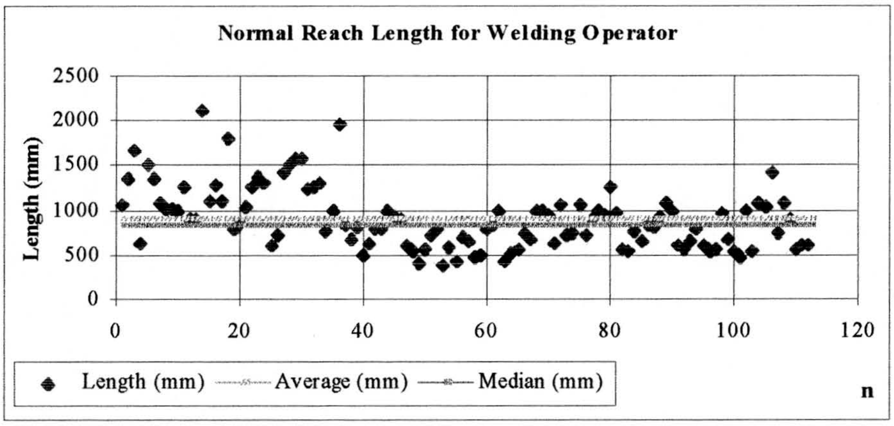

Figure 1.7 Recorded Data Plot of Normal Reach

F .1.6. Normal Welding Current Settings

F .1.6.1. *Welding Current Settings for 1.6 mm Flux Core Wire*

Current Setting 1.6 mm Wire = 268 Ampere (down-hand). The welding current setting for the 1.6 mm flux core wire was determined by taking the median of the recorded data. Operator Setting referred to the welding settings used by the operator with which he feels comfortable with.

n	Operator Volt (V) Setting	Operator Current Setting (A) DC
1	31	250
2	29	345
3	32	320
4	29	290
5	31	340
6	29	250
7	41	330
8	31	335
9	35	230
10	29	240
11	32	250
12	26	310
13	31	260
14	27	310
15	29	240
16	36	290
17	26	250
18	32	250
19	25	256
20	28.5	280
21	30	205
22	35.5	300
23	30	310

24	32	380
25	30	290
26	21.5	210
27	27.5	230
28	26	320
29	35.5	360
30	27	276
31	28.5	300
32	28	220
33	25	320
34	27	260
35	29.5	250
36	31	300
37	30	230
38	31.5	330
39	31	230
40	29	260
41	29.5	260
42	26	230
	Average Welding Current	281.6285714
	Median Welding Current	268
	Standard Deviation	43.77673399

Table 1.8 Recorded Welding Current and Volts of Operators

F .1.6.2. *Welding Current Settings for 1.2 mm Flux Core Wire*

Current Setting 1.2 mm Wire = 190 Ampere (down-hand). The welding current setting for the 1.2 mm flux core wire was determined by taking the median of the recorded data.

n	Operator Volt (V) setting	Operator Current Setting (A) DC
1	24	140
2	27	200
3	32	150
4	30	150
5	30.5	150
6	32	190
7	34	190
8	33.5	190
9	30	200
	Average Welding Current	173.3333333
	Median Welding Current	190
	Standard Deviation	25

Table 1.9 Recorded Welding Current and Volts of Operators

F .1.7. **Electrode Change Time for Flux Core Arc Welding.**

Electrode Change = 685 seconds. The electrode Change time was determined by taking the median of the recorded times. The median value gave the smallest errors when predicting the recorded data.

n	Time	Seconds	Average (s)	Median (s)	Error of Average	Error of Median
1	12:27.0	747	696	685	-7%	-8%
2	11:05.0	665	696	685	5%	3%
3	09:58.0	598	696	685	16%	15%
4	11:25.0	685	696	685	2%	0%
5	12:35.0	755	696	685	-8%	-9%
6	12:33.0	753	696	685	-8%	-9%
7	11:09.0	669	696	685	4%	2%
				Average Absolute Error	6.99%	6.65%
				Cumulative Error	0.00%	-1.58%
				Standard Deviation	8.86%	8.72%
				Median of Error	1.61%	0.00%
				Confidence		
				90%	5.51%	5.42%

Figure 1.8 Recorded, Average and Median Electrode Change Times

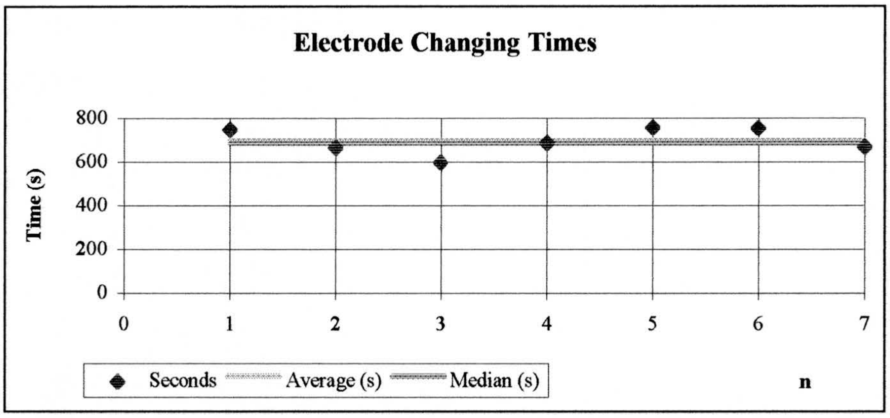

Figure 1.9 Recorded Data Plot of Electrode Change Times

F .2. Constants and Terms for Back Gouging of Welded Sections

F .2.1. Gouging Depth and Width vs. Number of Passes Required

Summary of the gouging depth and width vs. the number of gouge passes required in order to ensure accessibility for welding. The median depth values should be used to determine the number of passes required.

Passes	Average Depth (mm)	Average Width (mm)	Median Depth (mm)	Median Width (mm)
1	6.5	12.666667	6.5	13
2	11.666667	13.666667	11	13.5
3	16.333333	19.666667	16.5	19.5
6	25.5	25.833333	25.5	25
9	36.5	30.5	35.5	30
12	43.666667	30.166667	44.5	30

Table 2.1 Gouging Passes Required for Specified Depth

The area of the gouge section is determined by the required depth of gouging and assuming the area to take the shape of a parabola.

F .2.2. **Area Removed per Gouging Pass (for a given depth).**

Area Removed Per Pass = 102.58 square mm. The total area removed was determined by assuming a parabola shape of the cross sectional area of the gouged section. The area per pass removed was then determined by dividing the total area by the amount of gouging passes required. The median value of the are per pass were then taken. The median value gave the smallest errors when estimating the recorded data.

				ax^2+bx+c					
n	Width (mm)	Depth (mm)	Passes	a	c	Total Area Removed	Area Removed Per Pass (mm^2)	Error of Average Area Removed per Pass	Error of Median Area Removed per Pass
1	12	8	1	-0.2222	8	96	96	0%	0%
2	13	7	1	-0.1657	7	91	91	0%	0%
3	13	5	1	-0.1183	5	65	65	0%	0%
4	12	6	1	-0.1667	6	72	72	0%	0%
5	13	6	1	-0.142	6	78	78	0%	0%
6	13	7	1	-0.1657	7	91	91	0%	0%
7	14	11	2	-0.2245	11	154	77	0%	0%
8	13	11	2	-0.2604	11	143	71.5	-50%	-50%
9	13	11	2	-0.2604	11	143	71.5	-50%	-50%
10	15	13	2	-0.2311	13	195	97.5	0%	0%
11	13	11	2	-0.2604	11	143	71.5	-50%	-50%
12	14	13	2	-0.2653	13	182	91	0%	0%
13	20	17	3	-0.17	17	340	113.33333	0%	0%
14	22	16	3	-0.1322	16	352	117.33333	0%	0%
15	22	15	3	-0.124	15	330	110	0%	0%
16	19	17	3	-0.1884	17	323	107.66667	0%	0%
17	18	16	3	-0.1975	16	288	96	0%	0%
18	17	17	3	-0.2353	17	289	96.333333	0%	0%
19	29	28	6	-0.1332	28	812	135.33333	33%	33%
20	28	24	6	-0.1224	24	672	112	17%	17%
21	24	27	6	-0.1875	27	648	108	0%	0%
22	24	28	6	-0.1944	28	672	112	17%	17%
23	25	23	6	-0.1472	23	575	95.833333	0%	0%
24	25	23	6	-0.1472	23	575	95.833333	0%	0%
25	30	38	9	-0.1689	38	1140	126.66667	22%	22%
26	29	36	9	-0.1712	36	1044	116	11%	11%
27	26	42	9	-0.2485	42	1092	121.33333	22%	22%
28	34	35	9	-0.1211	35	1190	132.22222	33%	33%
29	34	34	9	-0.1176	34	1156	128.44444	22%	22%
30	30	34	9	-0.1511	34	1020	113.33333	11%	11%
31	30	38	12	-0.1689	38	1140	95	-8%	-8%
32	29	46	12	-0.2188	46	1334	111.16667	8%	8%

33	26	42	12	-0.2485	42	1092	91	-8%	-8%
34	34	45	12	-0.1557	45	1530	127.5	25%	25%
35	32	47	12	-0.1836	47	1504	125.33333	25%	25%
36	30	44	12	-0.1956	44	1320	110	8%	8%
							Average Absolute Error	11.73%	11.73%
							Cumulative Error	9.09%	9.09%
							Standard Deviation	19.50%	19.50%
							Median of Error	0.00%	0.00%
							Confidence		
							90.0%	5.35%	5.35%

Table 2.2 Recorded, Average and Median Data For Area Removed

Average Area Removed Per Pass	101.962963	mm^2
Median Area Removed Per Pass	102.583333	mm^2

Table 2.3 Average and Median Area Removed Per Gouging Pass

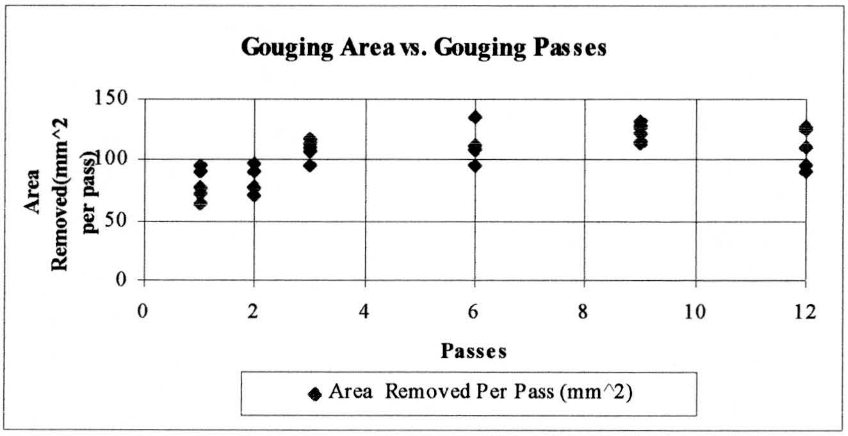

Figure 2.1 Gouging area removed per pass vs. passes

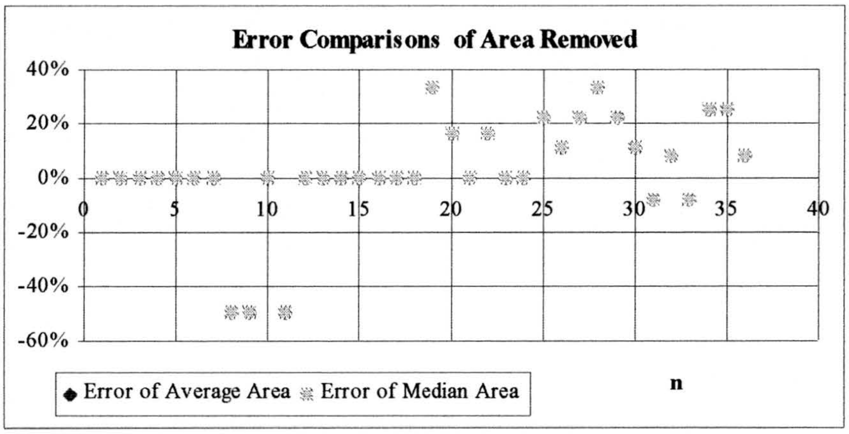

Figure 2.2 Error Comparisons for Area Removed

F .2.3. Gouging Setup Time

Gouging Setup = 55 seconds. The gouging setup was determined by taking the median of the recorded data. The setup time only occurs once for gouging and has very little influence over the total gouging time, especially when the gouge section gets longer and deeper.

n	Second	Average (s)	Error of Average	Median (s)	Error of Median
1	55	56.33333333	2%	55	0%
2	88	56.33333333	36%	55	38%
3	26	56.33333333	117%	55	112%
		Average	52%	Average	50%

Table 2.4 Recorded Average and Median Setup Times

F .2.4. Gouging De-Setup Time

Gouging De-Setup Time = 12 seconds. The gouging de-setup was determined by taking the median of the recorded data. The setup time only occurs once for gouging and has very little influence over the total gouging time, especially when the gouge section gets longer and deeper.

n	Second	Average	Error of Average	Median	Error of Median
1	11	12.66666667	15%	12	9%
2	12	12.66666667	6%	12	0%
3	15	12.66666667	16%	12	20%
		Average	12%	Average	10%

Table 2.5 Recorded Average and Median De-Setup Times

F .2.5. Gouging Time for a Single Pass

Gouging Speed = 0.272·L+135 seconds with L in [mm] and 380≤L≤10200.

The gouging time is defined as the cleaning, electrode change and arc time. The gouging time formula was determined with the least square fit method. The least square equation gave the smallest errors over the gouging length range when used to estimate the recorded data.

n	Combined Time		Length (mm)	Seconds	Speed (mm/min)	Median Speed Estimated Time (s)	Lest Square Fit Estimated Time (s)	Error of Median	Error of Least Square Fit
1	14:26.0		1100	866	76.212	439.093	433.308	-49%	-50%
2	0:04:35		800	275	174.545	319.341	351.849	16%	28%
3	05:18.0		800	318	150.943	319.341	351.849	0%	11%
4	06:45.0		940	405	139.259	375.225	389.864	-7%	-4%
5	04:35.0		800	275	174.545	319.341	351.849	16%	28%
6	03:18.0		380	198	115.152	151.687	237.807	-23%	20%
7	02:45.0		380	165	138.182	151.687	237.807	-8%	44%
8	03:02.0		380	182	125.275	151.687	237.807	-17%	31%
9	08:18.0		870	498	104.819	347.283	370.856	-30%	-26%
10	03:40.0		850	220	231.818	339.299	365.426	54%	66%
11	05:40.0		850	340	150.000	339.299	365.426	0%	7%
12	01:57.8		851	339	150.619	339.699	365.697	0%	8%
13	30:26.0	16:39.0	10200	2825	216.637	4071.593	2904.227	44%	3%
14	32:30.0	16:52.0	10200	2962	206.617	4071.593	2904.227	37%	-2%
							Average Absolute Error	21.71%	23.35%
							Cumulative Error	18.93%	0.00%
							Standard Deviation	29.12%	28.68%
							Median of Error	0.00%	9.26%
							Confidence		
							90%	12.80%	12.61%

Table 2.6 Recorded, Median and Least Square Estimated Data for Gouging Time

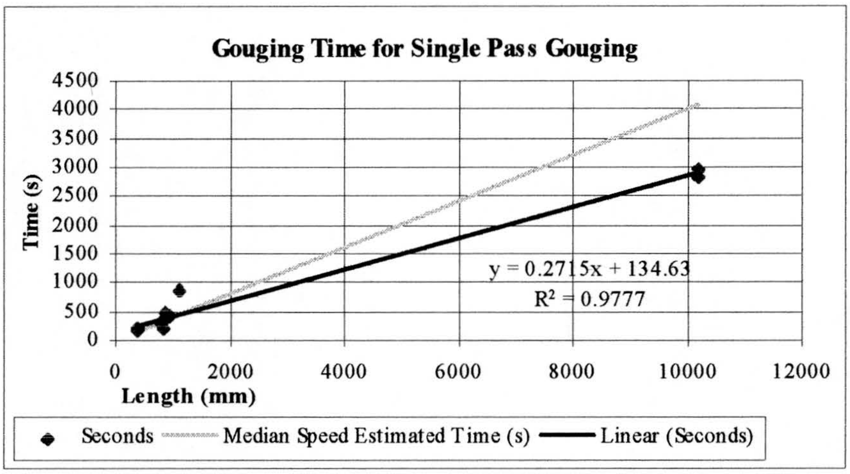

Figure 2.3 Single Pass Gouging Time vs. Length

F .2.6. **<u>Gouging Rod Usage (for single pass).</u>**

Gouging Rod Usage = 2.249 mm gouged per m of rod. The rod usage was determined by taking the median of the recorded rod usage's data. The median gave the smallest errors in predicting the amount of gouging rods required.

n	Length (mm)	Gouging Rods Used	Length Gouged Per Rod, (mm/rod)	Total Length of Gouging Rod Required (mm)	Gouging Usage (mm Gouged) /(mm Rod)	Average (mm Gouged) /(mm Rod)	Median (mm Gouged) /(mm Rod)	Error of Average	Error of Median
1	1100	2.875	382.609	647.62	1.69853	2.2013	2.249260	-23%	-25%
2	800	2.125	376.471	478.68	1.67128	2.2013	2.249260	-24%	-26%
3	800	2.375	336.842	534.99	1.49535	2.2013	2.249260	-32%	-34%
4	940	1.75	537.143	394.2	2.38455	2.2013	2.249260	8%	5%
5	800	2	400	450.52	1.77573	2.2013	2.249260	-19%	-22%
6	380	1.125	337.778	253.42	1.49951	2.2013	2.249260	-32%	-34%
7	380	0.75	506.667	168.94	2.24926	2.2013	2.249260	2%	-1%
8	10200	16	637.5	3604.1	2.83007	2.2013	2.249260	29%	25%
9	10200	17	600	3829.4	2.6636	2.2013	2.249260	21%	18%
10	380	0.625	608	140.79	2.69911	2.2013	2.249260	23%	19%
11	10200	16	637.5	3604.1	2.83007	2.2013	2.249260	29%	25%
12	10200	17	600	3829.4	2.6636	2.2013	2.249260	21%	18%
13	850	1.75	485.714	394.2	2.15625	2.2013	2.249260	-2%	-5%
							Average Absolute error	20.35%	19.66%
							Cumulative Error	17.05%	13.67%
							Standard Deviation	23.49%	22.82%
							Median of Error	2.18%	-0.77%
							Confidence		
							90%	10.72%	10.41%

Table 2.7 Recorded, Average and Median Data for Gouging Rod Usage

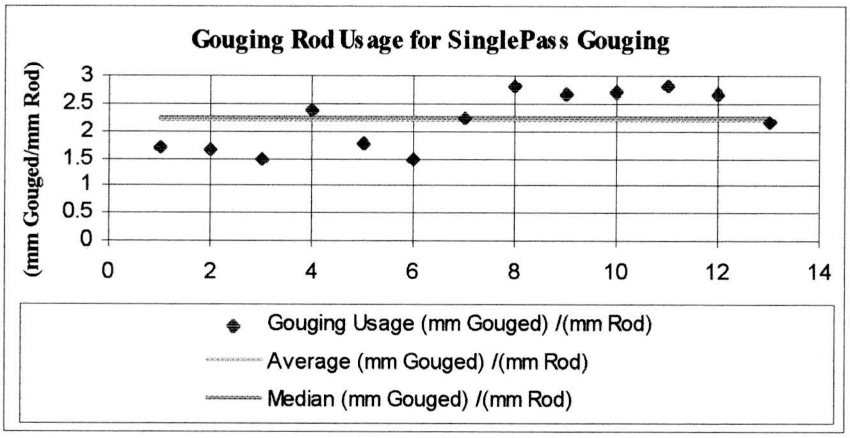

Figure 2.4 Recorded Data Plot of Gouging Rod Usage

Appendix G

Design Example

The design example considers the evaluation of two different design concepts which serve the same function, have the same weight and have the required strength. See Figure 1.

Concept-1

Comprises the use of two 150mm thick plates to produce a corner piece. The plate material purchased needs to be profiled into two separate identical parts. The two plates are then assembled and welded with a 40mm equal leg fillet weld.

Concept-2

Comprises the use of four 75mm thick plates to produce an identical corner piece. The plate material purchased therefore needs to be profiled into four separate identical parts. Each part then has to be bevelled in order to facilitate welding. For the purpose of illustration we have chosen a 30mm, 45 degree bevel, all around the part edge on one side only for all four of the parts. Two sub-assemblies are then formed by laminating two 75mm plates together, these sub assemblies are then welded. The two sub-assemblies are then assembled together and welded with a 40mm equal leg fillet weld.

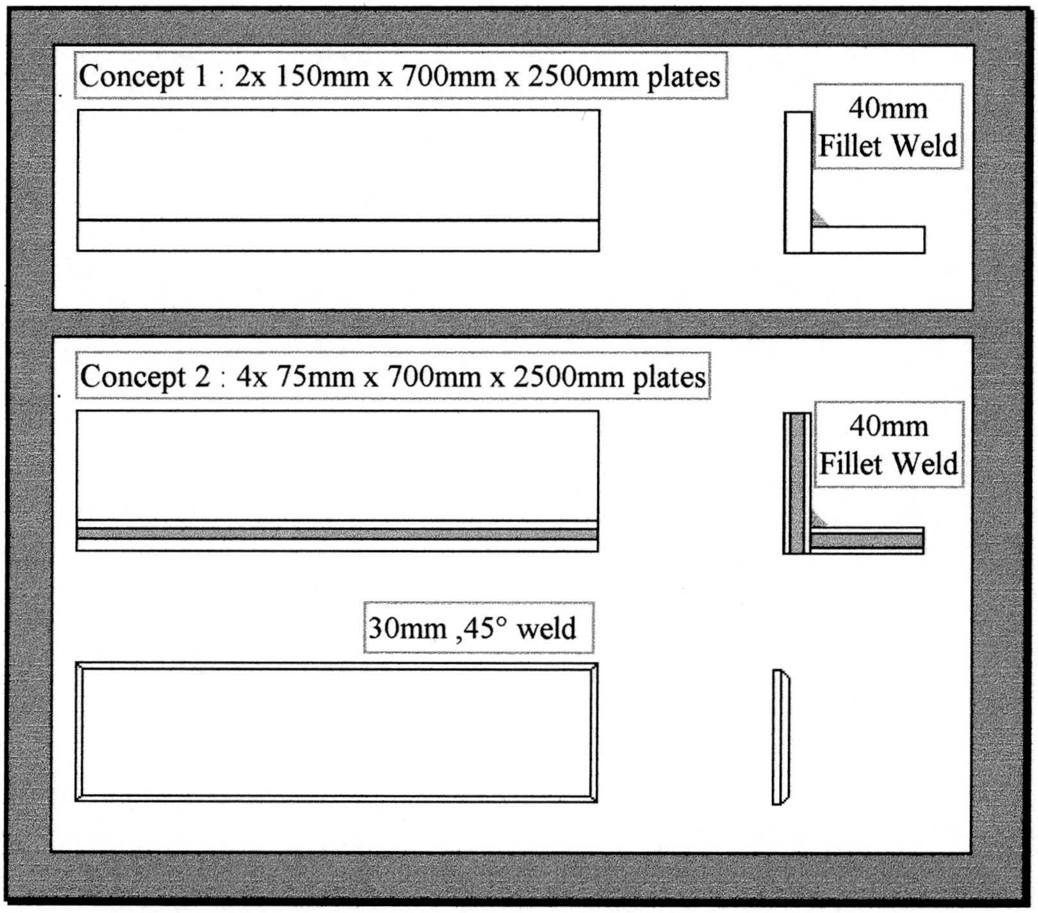

Figure 1 Two design concepts proposed. Both satisfy the same engineering requirements.

If it is known that both of these concepts satisfy the same requirements, then the designer can decide himself, which one of these two assemblies are the cheapest to produce and what alterations can be done to the design to lower the manufacturing cost of the cheapest option.

In practice one would only get accurate answers to this question by trial and error, which could be quite expensive. From the statement of the problem it can be seen that concept two would require more labour and probably would be the more expensive option.

The input requirements for the cost estimation models of the two design concepts are summarised in Table 1.

	Concept 1	Concept 2
CNC Profiling Production + Sub Processes		
Number of parts on Plate Material	2	4
Total Length to be Cut	12,000 mm	27,000 mm
Number of Internal Features	0	0
Dimension 1 of Plate Material Purchased	2,700 mm	2,700 mm
Dimension 2 of Plate Material Purchased	1,700 mm	3,300 mm
Material Thickness	150 mm	75 mm
Make 100mm allowance in between and around parts		
Bevelling Production + Sub Processes		
Number of Single Bevels Per Part	N/A	4
Bevel 1 , Mechanised, Face Width of 42.4 mm	N/A	2,500 mm
Bevel 2 , Mechanised, Face Width of 42.4 mm	N/A	2,500 mm
Bevel 3 , Mechanised, Face Width of 42.4 mm	N/A	700 mm
Bevel 4 , Mechanised, Face Width of 42.4 mm	N/A	700 mm
Single Bevels on Both Sides of Part	N/A	No
Storage Distance	N/A	20 m
Manual Assembly		
First Level of Assembly		
Number of Parts	2	4
Weight of Part	500 kg	240 kg
Joining Length	2,500 mm	7,000 mm
Number of Joining Lines	1	4
Part Curved	No	No
Material Thickness	150 mm	75 mm
Distance from Storage	20 m	20 m
Second Level of Assembly		
Quantity Of Parts	N/A	2
Weight of Part	N/A	500 kg
Joining Length	N/A	2,500 mm
Number of Joining Lines	N/A	1
Part Curved	N/A	No
Material Thickness	N/A	150 mm
Distance from Storage	N/A	20 m
Welding Production + Sub Processes		
Number of Different Weld Sections	1	3
Weld Section 1, Fillet Weld, Area	800 mm^2	800 mm^2
Weld Section 1, Fillet Weld, Length	2500	2,500 mm
Quantity on Assembly	1	1
Weld Section 2, Custom, Area	N/A	900 mm^2
Weld Section 2, Custom, Length	N/A	2,500 mm
Quantity on Assembly	N/A	4
Weld Section 2, Custom, Area	N/A	900 mm^2
Weld Section 2, Custom, Length	N/A	700 mm
Quantity on Assembly	N/A	4
Operating Factor	0.18	0.18
Deposition Rate (from manufacturer data)	3.67 kg/hr	3.67 kg/hr
No Sub Process Parameters Specified for Welding		

Table 1 Summary of inputs for the two concepts.

The result given by the cost estimation models can then be summarised as follows :

The production time associated with each manufacturing process involved is directly obtained from the cost models and are:

	Concept 1 (2X150mm)	Concept 2 (4X75mm)	
CNC Labour Time	2.59	3.97	hrs.
CNC Secondary Time	0.23	0.50	hrs.
Bevelling Time	0.00	3.31	hrs.
Bevelling Secondary Time	0.00	0.87	hrs.
Assembling Time	1.9	6.46	hrs.
Welding Time	21.33	144.23	hrs.
Total Production Time	**26.05**	**159.34**	**hrs.**

The volume of material required is determined from the material purchases. Concept one requires a larger volume of material due to a 100 mm allowance for profiling around and in between parts. The electrode weight required are determined directly from the Welding Cost Estimation Model.

Vol. Material Required	0.6885	0.66825	m^3
Electrode Required	19.59	132.43	kg

The labour rate per hour can then be obtained from the financial department and electrode and material costs can be obtained from suppliers relatively easy. The huge difference between the R/Ton value of the two materials used in the example can be contributed to the availability of the material, the 150 mm material need to be imported.

Labour Rate	Electrode Cost	
R110.00	R14.00	R/kg

Material Cost		
R15,779.20	R/Ton	150 mm
R10,917.00	R/Ton	75 mm

The labour rate, electrode and material costs can then be combined with the labour times and material and electrode requirements to obtain the cost of each concept.

Labour Cost	R2,865.50	R17,527.40
Material Cost	R85,130.14 [1]	R57,165.86
Electrode Cost	R274.26	R1,854.02
Total Cost	**R88,269.90**	**R76,547.28**

Saving	R0.00	R11,722.62
% Saving	**0%**	**13.28%**

From the aforementioned it is clear that the second concept is the cheapest to produce, which proves that "part count" reduction and shorter labour time does not always give the best solution. The main cost driver of the first concept is the material cost. The main cost driver of the second concept is the material and then labour cost. The main contributor to the labour cost of the second concept is welding production. The designer can now optimise in these cost regions to obtain the most cost effective concept.

Of all the labour times of concept two, welding is the highest and the designer can now endeavour to reduce this by specifying a smaller bevel size on the 75mm plates. If he reduces the bevel angle on one plate from 45° to 30°, he then reduces the electrode required to 84.74 kg and the time required for welding to 92.34 hours while maintaining the quality of the weld section and accessibility for welding. The grinding time required for bevel cleaning also decreases to 0.83 hours. With all new data included into the cost model we get a 20.5% saving over the first concept and a 8.3% saving over the second concept just by employing design optimisation. Forethought in the design stage can produce considerable cost savings.

[1] Steel Density of 7836 kg/m^3 used

Appendix-H

Statistical Methods and Descriptions

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H.1. Formula Construction

Time formulas are applicable to practically all work. If sufficient time studies are collected to give a reliable sampling of data, it is possible to design a formula for a given range of work in any type of job. In addition, specific information about the variable time elements, such as surface area, length , material thickness, weight etc. must also be included. Analysts should apply the formula only to jobs that fall within the limits of the data used in developing it. If they exceed the boundaries of the formula without the supporting proof of individual time studies, erroneous standards, with all the dangers brought about by inequitable rates, may result.

A time study formula must be completely reliable and practical if it is to be used with confidence. The formula also gives as accurate results as the data used to construct it. A practical formula is clear, concise, and simple as possible. The limitations of the formula must be noted by describing in detail its applicable range.

H.1.1. Least Squares Techniques

To determine whether an element is variable, it is whose to plot the recorded times vs. its designated variable (e.g. time vs. length). An increase in time with an increase in length indicates a relationship between time and length which is, in most cases, linear. Other trends (e.g. power trend) were also used. The derivation principle used to determine the constants for these fits is identical to that of a straight line.

We are interested in determining the equation of a straight line that best fits the data. By best fit, we mean the equation of the line $y=mx+c$, where the sum of all the squared vertical distances $(y_i - y)$ for the points comprised by the data is a minimum. Hence, we want to minimise the error term $(y_i - y)^2$.

The nominal equations involving the parameters m and c whose values for the line of best fit of the data are then determined by setting the partial derivatives for minimising the coefficient equal to zero and solving the equations simultaneously.

The error term that we want to minimise is:

$$\sum_{i=1}^{n}(y_i - (m \cdot x_i + c))^2$$

The derivatives with respect to m and c are then:

$$\sum_{i=1}^{n} y_i = c \cdot n + m \cdot \sum_{i=1}^{n} x_i$$

$$\sum_{i=1}^{n} y_i \cdot x_i = c \cdot \sum_{i=1}^{n} x_i + m \cdot \sum_{i=1}^{n} x_i{}^2$$

These equations can readily be solved simultaneously to provide the numerical values of the slope m and the y intercept c.

The goodness of fit is used to measure the linear correlation of data with the equation of the straight line that best fits the plotted data. The correlation coefficient is:

$$r = \frac{Sxy}{Sx \cdot Sy}$$

where:

$$Sx^2 = \frac{1}{n} \cdot \sum_{i=1}^{n}(x_i - \bar{x})^2$$

$$Sy^2 = \frac{1}{n} \cdot \sum_{i=1}^{n}(y_i - \bar{y})^2$$

i.e. the sample variances[1]

[1] $\bar{x}$ is the mean, and are calculated by $\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i$

$$Sxy = \frac{1}{n} \cdot \sum_{i=1}^{n} (x_i - \bar{x}) \cdot (y_i - \bar{y}) \qquad \text{the covariance}$$

If r is positive, it indicates that the data are positively correlated, i.e. the regression line slope is positive and vice versa; if |r|=1 then we have perfect correlation with all plotted points lying on the regression line. If r=0 then the variates are not linearly correlated.

H.1.2.Multiple Linear Regression

At times there are more than one independent variable that influences the dependant variable (time). If two independent variables are involved in a linear relationship, then we are fitting a plane to a set of n points to minimise the sum of the squares of the vertical distances from the points to the plane. Thus we are minimising the term:

$$\sum_{i=1}^{n} \left[y_i - (c + m_1 \cdot x_i + m_2 \cdot z_i) \right]^2$$

By setting the partial derivatives with respect to the coefficients equal to zero we are minimising the error term and hence, obtain the following normal equations:

$$\sum_{i=1}^{n} y_i = n \cdot c + m_1 \cdot \sum_{i=1}^{n} x_i + m_2 \cdot \sum_{i=1}^{n} z_i$$

$$\sum_{i=1}^{n} y_i \cdot x_i = c \cdot \sum_{i=1}^{n} x_i + m_1 \cdot \sum_{i=1}^{n} x_i^2 + m_2 \cdot \sum_{i=1}^{n} x_i \cdot z_i$$

$$\sum_{i=1}^{n} z_i \cdot y_i = c \cdot \sum z_i + m_1 \cdot \sum_{i=1}^{n} z_i \cdot x_i + m_2 \cdot \sum_{i=1}^{n} z_i^2$$

These equations can now be solved simultaneously to obtain the constants c, m_1 and m_2.
This illustrates the multiple regression technique, the procedure can be easily adapted for more than two independent variables.

The least square goodness of fit is also applicable for multiple linear regressions and the interpretation is the same.

H.1.3. Robust Data Analysis (Resistant lines for y vs. x)

The best known and most widely known method to fit a straight line through a set of data points is the least squares method. Unfortunately, the least squares regression line offers no resistance. A wild data point can easily seize control of the fitted line and cause it to give a totally misleading summary of the relationship between x and y [Hoaglin, 1982].

The basic idea is to divide n data points into three groups, use medians to form a summary point within each group, and base the line on these three summary points.

The n data point are divided into three groups (left, middle and right) as nearly equal in size as possible. Ties among x_i may prevent us from achieving precisely this allocation. All values with the same x-value goes into the same group. Within each of these groups we determine the co-ordinates of a summary point by first finding the x-median value and then separately the y-median value. We label these points L (left), M (middle) and R (Right). As long as the number of data points within each group is not to small, then the median provides resistance to wild values of x and y, or both.

If it can be assumed as realistic for the intercept to be close to 0 then the initial slope is determined by:

$$m = \frac{y_R - y_L}{x_R - x_L}$$

By using this relation we strike a balance between:

1. the advantage of measuring the change in y over a wide interval of x and
2. the need to have enough data in the left and right groups for adequate resistance.

When we use the fitted slope to adjust the y-value of each summary point, the remainder is the intercept value for a line of slope m that passes exactly through that point. The fitted intercept is the average of these three values:

$$c = \frac{1}{3} \cdot \left[(y_L - m \cdot x_L) + (y_M - m \cdot x_M) + (y_R - m \cdot x_R) \right]$$

Because the summary points are based on medians, c is resistant.

The above mentioned equation has little relevance when the x-values lies far from zero. For such situations we use fittings in terms of slope and central value, where the central value is at the median of all the x-values or at the x_M value. If we work at $x = x_M$ then the slope will be as before and the central value c is:

$$c = \frac{1}{3} \cdot \left[(y_L - m \cdot (x_L - x_M)) + y_M + (y_R - m \cdot (x_R - x_M) \right]$$

Once the slope and level for the fitted line, the immediate next step is to calculate the residual for each data point:

$$r_i = y_i - \left[c + m \cdot (x_i - x_M) \right]$$

If we substitute these residuals for the original y-values of our data set and repeat the fitting process, and the new slope and intercept yields a zero result. Then we know that residuals contain no further straight-line behaviour. If the opposite is true then we need to adjust the initial slope and intercept values with the newly determined ones for the residuals and repeat the iteration process. In practice the iteration is continued until the adjustment to the slope is less than 1% (preferably 0.01%) of the size of c. This technique ensures an even scatter of residuals.

H.2. Description of terms used in this thesis

H.2.1. Average Values

The average for a set of n data points is defined as:

$$average = \frac{\sum_{i=1}^{n} x_i}{n}$$

The average absolute error is therefore:

$$average = \frac{\sum_{i=1}^{n} |x_i|}{n}$$

H.2.2. Median Values

The median is the number in the middle of a set of numbers; that is, half the numbers have values that are greater than the median and half have values that are less. This offers resistance to wild data points.

H.2.3. Standard Deviation

The standard deviation is a measure of how widely values are dispersed from the average value (the mean). It is also called the standard error of the estimate [O'Connor, 1991]

H.2.4. Confidence

The confidence interval is a range on either side of a sample mean. For example, if you order a product through the mail, you can determine, with a particular level of confidence, the earliest and latest the product should arrive. The confidence is based on the assumption that all distributions are Normal or Gausian distributions. In this thesis the confidence limit implies the interval between the upper and lower limits and will include the true value [O'Connor, 1991]. For example, I can say with 90% certainty that the part removal time for the CNC flame profile cutting process will be within a 10% interval of the estimated figure.